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Editorial

Resilience by Design: What Holds, Who Decides, and What Breaks in an Age of Systemic Risk

This issue of *LABSREVIEW* makes a claim without dressing it up: resilience is not something systems “develop” over time. It is something they either earn through design or lose through design shortcuts that look harmless until conditions change. In an era when shocks travel fast and compound quickly, resilience is less a future ambition than a present test of legitimacy.

At first glance, Volume 2, Issue 2 looks wide-ranging: numerical analysis, sustainable finance, social entrepreneurship, and digital public governance. The variety is real. So is coherence. Each contribution interrogates the same modern vulnerability: we now depend on instruments, models, metrics, frameworks, and technologies that promise stability, credibility, or efficiency while narrowing the conditions under which those promises remain true. When capacity is uneven, incentives misalign, and oversight lags, fragility does not announce itself. It performs. It produces plausible outputs right up to the moment it fails.

What makes this type of failure difficult to govern is its procedural character. Breakdown arrives through a rating rubric that quietly rewards the wrong behavior, a sustainability signal that becomes strategy rather than substance, a partnership that exists only at the level of language, or a digital system that restricts participation by design. Accountability blurs because decisions migrate into technical vocabularies and delegated infrastructures. Outcomes remain visible; the machinery producing them becomes harder to see, question, or contest. Under those conditions, resilience becomes inseparable from transparency, contestability, and institutional responsibility.

Díaz’s paper anchors the issue in the most concrete sense of stability. In numerical analysis, convergence is not rhetoric; it is the difference between methods that can be trusted and methods that only behave under friendly assumptions. Díaz advances a sixth-order iterative family and tests more than speed or elegance. The work maps where the method holds and where it collapses. That stance matters beyond mathematics. It models a discipline that, in sustainability work, often needs designs to be evaluated under variation, not validated under ideal conditions. If a method cannot tolerate imperfect starting points, it will not tolerate reality.

Finance brings the same question into institutional form. Momo-Dino’s study places ESG inside the credibility machinery that structures modern markets. The importance of ESG here is not symbolic. It is operational. It shapes rating judgments, reputational capital, and access to financing, the channels that define what firms can do and what they can justify. The study also refuses a convenient simplification. ESG aligns with stronger credit ratings while coinciding with pressure on short-run operating performance. That tension is the point. Sustainability, in practice, often requires investment before it yields conventional returns. The credibility benefit may arrive sooner than the earnings benefit. Any serious resilience agenda has to deal with that sequencing rather than deny it.

The deeper issue is that credibility systems do not simply describe firms; they train them. Once metrics gain authority, behavior reorganizes around them. Organizations optimize what gets scored. They learn which signals to travel and which do not. That can push systems toward durable value when evaluation captures real risk and real impact. It can also produce a thin, performative compliance when evaluation rewards what is legible rather than what is consequential. The question of resilience, then, is not whether sustainability can be measured. It is whether measurement regimes can withstand strategic behavior, unequal capacity, and shifting incentives without becoming theater.

Medine et al. turn from financial credibility to institutional coordination, and they name a familiar failure mode with unusual clarity: fragmentation produces fragility. Their Transformational Theory of Change does not function as another planning template. It functions as an insistence that resilience depends on coordination across sectors and levels, with government, business, and social-sector organizations acting with shared commitments rather than parallel intentions. In this frame, co-creation is not a motivational slogan. It is an institutional requirement.

That requirement has teeth. Collaboration tends to be celebrated as consensus, but it operates as negotiation: over authority, resources, timelines, standards of proof, and responsibility when outcomes disappoint. Durable co-creation requires structures that outlive personalities and funding cycles, rules that bind, data that can be shared

without capture, and accountability that does not dissolve the moment a partnership becomes inconvenient. Resilience does not come from launching initiatives. It comes from keeping agreements enforceable when conditions stop cooperating.

Morales-Acevedo et al. bring the issue to its sharpest edge by confronting digital governance as power governance. Their argument rejects the comforting assumption that digitization equals modernization. Emerging technologies reshape who can participate, who gets classified, who receives services, and who remains exposed. They can widen access, yet can also harden exclusion. They can enhance efficiency yet also normalize surveillance, deepen dependency, and reproduce bias through automated decisions that appear neutral because they are technical. The difference lies in capacity, regulation, and strategy, especially where territorial inequality and institutional weakness already structure outcomes.

The connective thread to the other papers is not abstract. A state can deploy advanced systems while losing legitimacy if oversight remains weak and decisions cannot be meaningfully contested. A market can reward ESG signals while leaving underlying harms intact. A development agenda can celebrate entrepreneurship while failing to build the governance arrangements that make collaboration durable. The instruments vary, but the pattern repeats: power moves into infrastructure, then disappears behind procedure.

Taken together, the issue advances in a single direction: resilience belongs to design, not slogans. It requires convergence under strain, credibility that does not collapse into signaling, co-creation that survives beyond programs, and digital governance that treats technology as a political force rather than a neutral tool. This is not a call for pessimism. It is a call for adult standards: stability must be demonstrated, trust must be earned through accountable systems, collaboration must be institutionalized, and digital transformation must be governed with safeguards rather than after-the-fact corrections.

This is also a statement about *LABSREVIEW*. The journal's purpose is not to publish sustainability as a theme alone, but to publish on the infrastructures that decide whether sustainability remains feasible: the methods that hold under disturbance, the metrics that discipline behavior, the institutional arrangements that coordinate action, and the digital systems that redistribute authority. These infrastructures determine what becomes fundable, governable, and just, often long before outcomes are measured.

In an age of systemic risk, resilience is no longer a comforting label. It is a standard. This issue invites readers to apply that standard where it matters most: to the architecture we build, the incentives we embed, and the forms of control we normalize. The final question is not whether resilience is desirable. It is whether the designs we adopt can carry the weight we now place on them, and whether those designs remain answerable to the people who live with their consequences.

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Article (Theoretical)

A theory of change framework for Caribbean resilience and sustainability through social entrepreneurship

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Abstract: Traditional sectoral efforts for social development (SD) in Latin America and the Caribbean have largely failed to produce significant results, prompting the introduction of the Transformational Theory of Change (TToC) as a new approach to address socioeconomic decline and environmental degradation while achieving SD and the Sustainable Development Goals (SDGs). This conceptual paper is grounded in a literature review of social entrepreneurship and effective sustainable development (SD) practices, which informs the development of the TToC. The findings emphasise the importance of a collaborative, multisectoral approach and the role of social enterprises in enhancing resilience and promoting national Sustainable Development (SD). However, such collaborative efforts are scarce in the Caribbean, highlighting the need for the Transformational Change Pathway (TCP) and Collaboration Relationship Enabler (CRE). This TToC is the first of its kind at the national level, advocating for entrepreneurial change at the organisational level to foster resilience, with the TCP and CRE enhancing its applicability and providing a model for SD in developing contexts. However, a key limitation is the lack of genuine collaboration between businesses, governments, and social sector organisations (SSOs), necessitating further research to validate the TToC and its supporting frameworks. By transforming SSOs into social enterprises, the Caribbean can enhance social sector resilience, thereby contributing to national Sustainable Development (SD) and the Sustainable Development Goals (SDGs), with potential applicability beyond the Region.

Keywords: Co-creational Process, Social Entrepreneurship, Theory of Change

1. Introduction

The economic downturn associated with COVID-19 led to Caribbean countries experiencing one of the worst social and economic disasters in over a century (ECLAC, 2022). Like other settings, COVID-19 curtailed business activities, resulting in increased closures, unemployment, and poverty, accompanied by increased social unrest, criminal activity, familial loss, and damage to the social structures that keep society together (ECLAC, 2022). These challenges compounded pre-existing societal threats such as environmental degradation related to climate change and flooding, land and property destruction, and animal and human displacements (Minto-Coy et al.,

2022). Traditionally, nonprofit organisations [NPOs] and other social sector organisations [SSOs] assist in alleviating these social and environmental ills and contribute to sustainable development (Samad et al., 2023). In developing countries, these third-sector organisations generally address gaps that the public and private sectors are unable to meet (Clear et al., 2018). However, in the Caribbean context, most of these organisations lack the resources and capabilities to address these challenges effectively (Bahaw et al., 2025b). These limits are further exacerbated by SSOs' financial dependence on donor organisations (Bowen, 2013; Medine & Minto-Coy, 2023). The global economic downturn, donors' financial constraints, and resultant funding reductions have placed SSOs at a crossroads, stretching their limited resource capabilities at a time when the need for their services has increased. The threat is reduced social impact, increased social unrest, and a threat to the realisation of the UN 2030 Sustainable Development Goals (SDGs), even as ineffectiveness and organisational closure are not viable options for national social development [SD]. The call is for newer, more sustainable models for survival.

As a cluster of small island developing states (Pounder, 2015), the Caribbean faces acute vulnerabilities (Minto-Coy et al., 2022). When combined with other challenges, such as crime and violence (seen as public health issues), these hinder social and economic development (Bisca et al., 2024). Within this myriad of challenges, the Government and business are tasked with meeting the SDGs.

1.1. Caribbean Economic Realities - SDGs

Realising the SDGs necessitates significant funding, estimated at around US\$100 billion for the coming decade (Leon, 2022). Regrettably, the Caribbean's challenging economic landscape makes this aspiration unfeasible. Table 1 (below) demonstrates that from 2017 to 2019, most Caribbean countries experienced declining GDP growth rates, with minor projected improvement for 2022 to 2026, except for Guyana. Moreover, the national debt-to-GDP ratio between 2015 and 2020 has consistently remained alarmingly high, reaching as high as 73.7% in 2019, exceeding the critical threshold of 55% of GDP, beyond which further debt accumulation has been noted to hinder economic growth (CMCA, 2021).

Table 1: Past Fiscal Space and Past/Future Growth Indicators in Selected Caribbean Countries

Past Fiscal Space and Past/Future Growth Indicators	Fiscal Imbalance/ GDP ratio			Real GDP growth (Annual per cent change)				
	2017	2018	2019	2022	2023	2024	2025	2026
Antigua and Barbuda	-2.4%	-2.3%	-3.6%	8.5	5.6	5.4	4.2	2.8
Bahamas	-5.6%	-3.4%	-1.7%	14.4	4.3	1.8	1.6	1.6
Barbados	-4.5%	-0.3%	3.7%	9.8	4.5	3.9	2.8	2.3
Belize	-1.3%	-1.2%	-4.6%	12.7	4	3	2.5	2.5
Dominica	-5.0%	-7.9%	-17.7%	5.7	4.6	4.6	4.2	2.9
Grenada	3.0%	4.9%	4.2%	6.4	3.9	3.8	3.5	3.2
Guyana	-4.5%	-3.3%	-3.5%	62.3	38.4	26.6	18.8	21.2
Jamaica	0.5%	1.2%	0.9%	5.2	2	1.8	1.7	1.6
Saint Kitts and Nevis	1.9%	3.2%	1.6%	8.8	4.9	3.8	3	2.7
Saint Lucia	-1.2%	-2.0%	-2.7%	15.7	3.2	2.3	2.3	1.8
Saint Vincent and the Grenadines	-2.2%	-1.6%	-3.0%	5.5	6.2	5	3.9	2.8
Suriname	-9.7%	-11.7%	-10.3%	1	2.1	3	3	3
Trinidad and Tobago	-8.9%	-3.6%	-2.4%	1.5	2.5	2.2	2.5	1.8
CMCA Caribbean Average	-3.1%	-2.1%	-2.9%	-	-	-	-	-

Source: CMCA (2021) and IMF World Economic Outlook (October 2023)

This reality underscores the Region's limited capacity for financing or for additional borrowing to invest in advancing SD. This reality can be juxtaposed with a decline in Official Development Assistance (ODA), a lack of transparency, and corrupt practices (Latindadd, 2022). Collectively, such challenges limit the effectiveness of public spending on SD (Gupta et al., 2002; Transparency International, 2021). Furthermore, with a score of 10.91 on its 2020 World Risk Index (CMCA, 2021), the Caribbean faces one of the highest levels of climate and disaster risk compared to other regions. Social decline, corruption, and environmental vulnerabilities significantly hinder the achievement of SD goals (Minto-Coy & Berman, 2016).

Pursuing resilience and sustainable growth and development is a priority among Caribbean Heads of State (ILO, 2022). Ultimately, at societal, national, and organisational levels, there is a need for developmental or transformational change to build what (Pinheiro et al., 2022) refer to as absorptive (ability to return to original states), adaptive (adjusting to change) and transformative (environmentally interactive change to a beneficial state) resilience. That is individual, societal, organisational, and national ability or resource capability to address adversity and become stronger and better.

Addressing this demand within the Caribbean's complex web of challenges necessitates a redefined approach to Sustainable Development (SD), with Social Entrepreneurship (SE) emerging as a promising solution (Bansal et al., 2019; UN, 2023). As a still emerging concept in the general entrepreneurship and innovation literature, social entrepreneurship (SE) refers to entrepreneurship applied in the social or public context (Dees, 2001). By creating and managing ventures that address community-based, social, or environmental challenges, social enterprises embody SE concepts that focus on maintaining a balance between social impact and financial viability (Teasdale et al., 2023; Saebi et al., 2019).

1.2. SE – International Context

The UN Inter-Agency Task Force (2019) advocates the social and solidarity economy, which leverages and embodies the principles of SE as essential for SD and the realisation of the SDGs. Guided by sectoral needs, grounded in empirical research, and supported by associated policies and institutional support, the EU has, for instance, leveraged social enterprise (the organisational form of SE – the social business) to drive sustainable development across Europe (OECD/EU, 2017). The view here is that social enterprises have the "potential to reshape the economy post-COVID through inclusive and sustainable economic models leading to a fairer ecological, economic, and social transformation" (European Commission, 2021, 4). In the international context, social enterprise operationalised via social enterprises is recognised as essential for rural, community, and societal development, as well as for building more resilient nations (Bernardion Santos, 2018; Bansal et al., 2019).

1.3. SE – Caribbean Context

Jamaica has led the way in the Caribbean, leveraging the inclusive approach of SE and social enterprise in engaging at-risk youth (DPIL, 2009), as well as community safety and security (Knife et al., 2018). The measurement of the effectiveness of social enterprises in generating value and monetising social value creation (Knife & Haughton, 2013) led to required institutional support (ICNL, 2018), the creation of the Jamaican Social Stock Exchange as a supportive financial instrument, and the determination of SSOs contribution to that country's overall GDP. These are important steps towards transforming SSOs into social enterprises, which are both operational and socially sustainable (Wendt, 2020).

The above, however, is not common across the Caribbean. Caribbean SSOs' abilities to address societal ills are hindered by donor dependency, limiting their operational and staffing capabilities (numbers and skills) (Medine & Minto-Coy, 2023). The same staffing challenges affect the ability to pursue earned income ventures for operational survival, with such income sometimes being subjected to standard taxation. The latter can deter income-generating pursuits (Stephens et al., 2024). Within these limitations, Caribbean SSOs are subject to anti-money laundering laws, with financial penalties for non-adherence (AML/CFT, 2015) and increased scrutiny due to their location in a region flagged for heightened financial risks. Notwithstanding, Medine & Minto-Coy's (2023) research demonstrated that NPOs operating as social enterprises with SE strategies have a greater potential of being operationally and financially sustainable in addressing their social missions.

1.4. Research Imperatives

This research builds on the achievements of social enterprises (Knife et al., 2018) in Jamaica, as well as Medine and Minto-Coy's (2023) findings on international best practices of SE for SSOs' sustainability and the UN Resolution A/77/L.60 of March 27, 2023. These streams of work reinforced social enterprise and social enterprises as a pathway for social transformation and the attainment of the SDGs. Importantly, they emphasise the importance of multisectoral collaboration. A direct outcome of Medine and Minto-Coy's work was the establishment of the first multisectoral committee in Trinidad and Tobago, the Social Entrepreneurship and Enterprise Development Steering (SEEDS) Committee (SEEDS Committee, 2023), to drive transformational change and support the development of social enterprises and the social economy. Integral to this group is the inclusion of academics across the Region, with SEEDS activities demonstrating a direct link between research and practice (Banasiewicz, 2021).

Thus, accepting SE as essential in building community and national resilience and recognising the limitations that transformational change is not a simple one-step or one-sector responsibility, this paper posits a

Transformational Theory of Change [TToC] model that leverages SE, leading to a resilient, entrepreneurial, self-sustaining social sector that contributes to sustainable national and regional socioeconomic and environmental development. The focus of the application is those Caribbean countries that are full members of CARICOM.¹ All Caribbean countries share a similar history, experience similar social and cultural issues, and face similar challenges in transitioning to sustainable economies and societies (Minto-Coy, 2015). Being members of CARICOM, they also have similar national policies addressing these challenges. Despite possible socioeconomic differences, given the universality of the SD challenges faced, there is an expectation that this TToC will be applicable to all Caribbean countries and other developing contexts with similar SD needs, including Latin America.

In deriving the TToC, we addressed the following research questions:

1. *How does Social Entrepreneurship build social sector resilience and support national social development?*
2. *What concepts underpin the effectiveness of Social Entrepreneurship as a foundational tool in the Theory of Change to build resilience and sustainable development?*

Section 2 provides a comprehensive review of the relevant literature, examining the dynamics and transformative potential of SE. It responds to the research questions while simultaneously ascertaining the conceptual foundation for this paper's proposed TToC model.

2. Materials and Methods

This conceptual paper synthesises theoretical and empirical insights to develop a novel framework integrating Social Entrepreneurship (SE), the Theory of Change (ToC), and Sustainable Development (SD). Given the interdisciplinary nature of our research, we employ an integrated literature review methodology (Jaakkola, 2020), which enables the synthesis of diverse theoretical perspectives while critically evaluating their applicability to our proposed Transformational Theory of Change (TToC) and Transformational Change Pathway (TCP). An integrated literature review is particularly suited to this study for three reasons. Firstly, this method facilitates the synthesis of interdisciplinary knowledge. Our research bridges SE, organisational change, and SD, requiring a methodology capable of consolidating insights from multiple domains (Snyder, 2019). Unlike systematic reviews that prioritise empirical uniformity, an integrated approach facilitates conceptual innovation by identifying intersections across disciplines (Snyder, 2019). Secondly, since our objective is to propose a new conceptual framework (the TToC and TCP), an integrated review enables us to "build on and extend existing theories rather than merely summarise them" (Jaakkola, 2020, p. 19). This method aligns with the theory-building purpose of our study, which facilitates theoretical development. Ultimately, the integrated literature review played a crucial role in helping us address gaps in developing contexts. Given the scarcity of Caribbean-specific entrepreneurship literature (Mack et al., 2025), an integrated review permits the inclusion of diverse sources (peer-reviewed studies, grey literature, case studies) to ensure contextual relevance while maintaining theoretical rigour (Bahaw et al., 2025c).

2.1. Literature Selection Process

To ensure robustness, we followed structured guidelines for literature selection (Podsakoff et al., 2005; Kraus et al., 2014) through:

Database Search: Source documents include peer-reviewed articles, books, white papers, and reports acquired from academic databases such as Google Scholar, Web of Science, EBSCOhost, and Scopus, as well as from reputable organizations like the European Union and the United Nations. Institutional reports (e.g., UN, EU) were included to capture policy and practitioner perspectives often absent in traditional journals. Restricting search to these validated sources assured academic rigour and information integrity.

Keyword Strategy: Keywords included "social entrepreneurship," "Caribbean," "resilience," "social development," "Theory of Change," "sustainability," and other related terms. These were selected to cover the broad topics of SE in developing regions and to refine the focus on best practices. Boolean operators (AND/OR) refined searches to balance breadth and relevance.

Inclusion Criteria: Articles were included based on relevance to social entrepreneurship, developing countries (particularly the Caribbean), resilience, and sustainable development. Considering SE as a developing

¹ Formed in 1973 and comprising mainly English-speaking Caribbean countries, CARICOM is a regional intergovernmental organisation aimed at promoting cooperation and economic integration among Caribbean states. Full members are Antigua and Barbuda, Bahamas, Barbados, Belize, Dominica, Grenada, Guyana, Haiti, Jamaica, Montserrat, Saint Kitts and Nevis, Saint Lucia, Saint Vincent and the Grenadines, Suriname, and Trinidad and Tobago.

concept and limitation on Caribbean research, we included publications from the past 25 years, ensuring the review reflects both past and contemporary challenges and practices in the field and accounts for SE's evolving conceptualisation.

Screening and Quality Assessment: We screened/accepted literature using titles and abstracts to filter for relevance to SE, ToC, and SD (conceptual and in-action) in developing and developed contexts, prioritising peer-reviewed sources that were ethically considerate and provided theoretical concepts, empirical insights, or case studies of social entrepreneurship practices relevant to our Region of focus. The steps followed during identification, screening, and inclusion are illustrated in the PRISMA-like flowchart (see Figure 1).

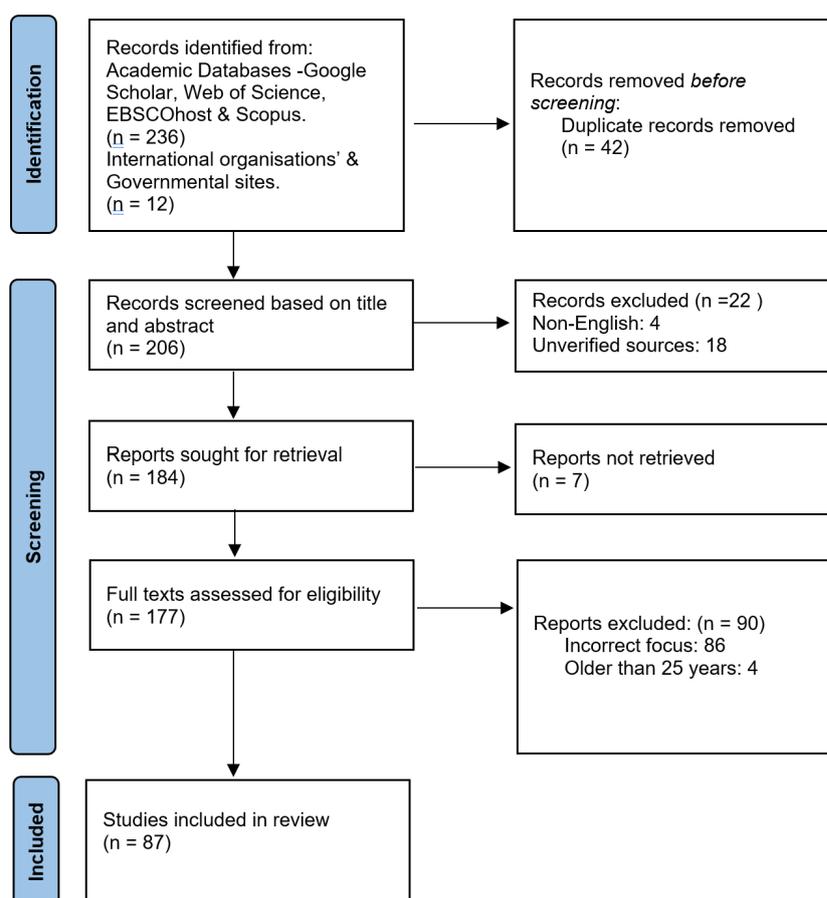


Figure 1. Modified PRISMA flowchart illustrating the literature selection process for the integrated review. Source: Adapted from PRISMA guidelines (Page et al., 2021).

2.2. Literature Analysis and Synthesis

To derive our conceptual framework, we employed:

Thematic Analysis for Framework Development: This involved categorising literature into themes (e.g., SE models, ToC operationalisation, collaboration barriers) to identify patterns and theoretical alignments (Braun & Clarke, 2006).

Cross-Referencing and Validation: We compared findings across developed and developing contexts to assess the applicability of existing theories and justify modifications (e.g., TCP and CRE components).

Critical Reflection: We noted limitations in current SE and ToC applications to underscore the need for our proposed TToC.

3. Results and Discussion

3.1. Social Entrepreneurship – Pathway to Development and Resilience

Entrepreneurship is not simply about starting a new business, but involves creative and innovative actions that generate value (Bacigalupo et al., 2016; Mack et al., 2024), particularly in the context of innovation management along the value chain of public, social, and business sector organisations (Bahaw, 2017; Drucker,

1993). Social entrepreneurship (SE) is a genre of entrepreneurship applied in the social or public context, operationalized via the social enterprise (Dees, 2001; Alter, 2007). It involves the application of business principles and innovative methods to address societal and environmental issues, thereby creating social value (Dees, 2007; Alter, 2007). As a developing concept and because social enterprises operate in nonprofit and for-profit sectors, there is often confusion between SE and the traditional NPOs, social activists, and corporate social responsibility (CSR).

Social enterprises differ from traditional nonprofits (NPOs), which rely on grants and donations (Alter, 2003). Social enterprises operate with dual financial and social missions, creatively leveraging resources, business tools, and techniques to create sustained social value (Alter, 2007). This is particularly relevant in resource-constrained environments, such as the Caribbean, where NPOs often face resource limitations (Medine & Minto-Coy, 2023). Furthermore, SE is not social activism, typically addressed without consideration of innovation or business principles (Medine & Minto-Coy, 2023). SE emphasises sustainable, transformative social change.

While CSR can create social value, the business's primary goal remains shareholder value, not social impact. CSR activities often align with business strategies or societal pressures rather than long-term social change (Gaither et al., 2018; Beg et al., 2023), for example. In the Caribbean, CSR actions are largely philanthropic (Arjoon & Ron Sookram, 2010), lacking a sustainable and systemic impact (Knife et al., 2018). Social value creation is not peripheral but central to SE (Dees, 2001; UN, 2016).

SE, the utilisation of business principles and innovation, i.e., SE strategies (Medine & Minto-Coy, 2023), can transform traditional NPOs and other SSOs into social enterprises, building organisational absorptive and adaptive resilience, enabling transformative resilience (Pinheiro et al., 2022) and achieving widespread social development from poverty and social justice to climate change, thereby creating lasting social value (Dees, 2001; Kim & Lim, 2017; Ito, 2017; Lubberink, 2019; Bansal et al., 2019). Hence, our focus is on the role of SE transformational value creation in addressing the socioeconomic ills noted in many Caribbean and other developing countries.

3.2. Social Entrepreneurship and Its Transformative Power

Globally, SE and social enterprises have been recognised as drivers of environmental and socioeconomic transformation (Anastasiadis & Mayr, 2009; Naderi et al., 2019), catalysing social development (Matei & Matei, 2012; Sharma, 2014). Such transformation involves addressing the root causes of social inequalities and problems rather than merely treating symptoms (Utting, 2018). Transformation is a collaborative process that engages stakeholders to achieve long-term, systemic cultural, social, and economic change (Crosby & Bryson, 2005). Such a collaborative approach to systematic transformational change begins with the social enterprise at the community or grassroots level, bringing about change to all levels of society (Rae, 2017). This SE's transformational foundation aligns with the UN Research Institute for Social Development's position on SE as being relevant and important to the Social and Solidarity Economy (SSE) and achieving the SDGs (Utting, 2018). Social enterprises invigorate communities by promoting inclusive and sustainable development through technological, social, and institutional innovations (Utting, 2015). With relevant institutional support, social enterprises are better equipped to withstand socioeconomic shocks and foster long-term resilience and SD (Haarich et al., 2020).

3.2.1 Supportive Institutional Support

Institutional support is crucial to SE's contribution to value creation and transformation. In countries like the United States, sectoral networks and supportive policies enhance the capacity of SSOs, enabling them to make significant contributions to the economy (Salamon, 2003). Similarly, an enabling ecosystem with skills development, policies, and legal frameworks in the EU has resulted in the transition of NPOs to social enterprises, contributing to national GDP, and making them leading job providers (OECD/EU, 2017). In the Caribbean, Jamaica provided appropriate institutional support, such as Social Impact Bonds (Mulgán et al., 2011) and the Social Stock Exchange, which enabled social enterprises to contribute to the national GDP (Knife et al., 2018). However, despite this positive move, institutional support in the Caribbean is still in its infancy, requiring more comprehensive multisectoral collaboration and limiting the operational sustainability of SSOs (CANARI, 2005; Comissiong, 2020).

3.2.2 Challenges in Collaboration and Support – Caribbean Context

Multisectoral collaboration for sustainable development (SD) in the Caribbean faces significant barriers. Although the Region has adopted SD policies with requirements for multisectoral collaboration, such as the OAS SD policies (General Assembly of OAS, 2012), implementation remains weak (CANARI, 2005; Comissiong, 2020). Governments view SSOs' contributions as tangential to central public sector goals, seemingly reluctant to fully embrace public-civil society partnerships, which hampers progress and Sustainable Development (Civil

Society Consultative Working Group, 2014). For example, although the Trinidad and Tobago government's post-COVID recovery strategy calls for increased SSO engagement (Ministry of Social Development and Family Services, 2022), much of the focus remains on incentivising the private sector and increasing donations to SSO rather than on genuine collaboration for SD. Similarly, ineffective collaboration exists between businesses and SSOs, whereby philanthropic actions and donations, not necessarily aligned to national developmental issues, are the primary forms of cooperation. Multisectoral, multidisciplinary collaboration with strategic information-sharing to inform decision-making ensures accountability and is essential for building national resilience; however, these elements are lacking in the Caribbean context (Zivkovic, 2011; ILO, 2020).

3.3 Building Resilience via Social Entrepreneurship

SE operationalised through social enterprises has the potential to strengthen social sector resilience and address SD challenges in the Caribbean (Betts et al., 2018; Diaz-Sarachaga & Ariza-Montes, 2022). However, sustained transformational change requires systematic transformational leadership and an enabling ecosystem (Muralidharan & Pathak, 2018; UN General Assembly, 2023). Transformational leadership, which involves collective stakeholder efforts and engagement, is key to driving sustainable entrepreneurial change. Sectoral or national resilience is not about replicating a single innovation, but rather the systematic management and synchronisation of context-specific innovations. By focusing on context-specific challenges and needs, transformational leadership can facilitate national resilience and sustainable change (O'Flynn & Wanna, 2008). This approach is particularly suited for developing countries, such as those in the Caribbean, where localised solutions are essential. International best practices suggest that policymakers play a central role in initiating and leading transformational processes, ensuring alignment with national Sustainable Development (SD) goals (OECD/EU, 2017). Their involvement in the Caribbean context is essential, given its size compared to other sectors (Minto-Coy & Berman, 2016). Irrespective, real change results from collaborative entrepreneurship in action (Bhutiani et al., 2012), which enables understanding of context-specific challenges, facilitates commitment, and leverages resources effectively (O'Flynn & Wanna, 2008). Leveraging the moral ethos of social entrepreneurship, transformational leaders with a forward-thinking vision and a holistic approach to sustainable development (SD) create scalable, sustainable solutions to global challenges (Marmer, 2012). Through the systematic, co-creational application of entrepreneurial activities, these leaders address environmental, societal, and economic issues, contributing to sustainable SD (Yoruk et al., 2022; Marchese et al., 2018).

Given SE's institutional nature (Popoviciu & Popoviciu, 2011), its solutions are context-specific, addressing the unique challenges of developing regions, such as the Caribbean (Bahaw et al., 2025a). The derived entrepreneurial solutions offer a more relevant approach to addressing development challenges than large-scale models, which may not adequately address local needs (Popoviciu & Popoviciu, 2011). While Caribbean nations have aligned their development plans with the Sustainable Development Goals (SDGs), collaboration remains insufficient (Gaither et al., 2018). Fragmented policies and reliance on donations cannot drive sustainable development or meet the Sustainable Development Goals (SDGs) (Utting, 2015). Meaningful, transformational change requires multisectoral input at all levels, i.e., context-driven change models or, as advocated in this paper, a Transformational Theory of Change [TToC] leveraging SE strategies to achieve SD.

3.4. Towards a Transformational Theory of Change Framework for Caribbean Resilience and Sustainability through Social Entrepreneurship

The ToC framework applies to all organisational or sectoral initiatives and interventions, customised by context and informed by evidence-based and best-practice research (Stein & Valters, 2012), elucidating a stepwise process of how a given intervention leads to specific developmental changes (UN, 2017). It helps define how interventions lead to outcomes and impact, mapping out the necessary steps and resources needed to achieve the desired change goal or impact. The process involves understanding the problem and desired outcomes, making assumptions, then defining the interventions, identifying the inputs (both tangible and intangible resources), and measuring the outputs, allowing for a direct measure of the effect or outcome. Measurement indicators with monitoring instruments enable stakeholders to track progress, measure outcomes, and determine the impact of processes and interventions. (Bacq, 2017; Goldsworthy, 2021; Reinholz & Andrews, 2020)

Despite conditional limitations, the ToC's systematic and structured processes facilitate understanding and acceptance of transformational change. The evidence-based feedback loops guide adjustments and reapplication, ensuring alignment with strategic intent and integrating multiple change levels, making the ToC an accepted planning and evaluation method for addressing and managing complex development problems, ideally suited to each Caribbean country's Sustainable Development (SD) initiatives. (Arensman et al, 2018; Stein & Valters, 2012b; Valters, 2014; Abercrombie et al, 2018). Notwithstanding, transformational change has transitional

challenges (Söderholm, 2020), which can be managed and synchronised with a defined transformational change pathway.

3.4.1. The Transformational Change Pathway

Achieving transformational change for social sector resilience and sustainable development is complex, requiring multilevel, context-specific changes tailored to that context and implemented through interlinked or interdependent Theories of Change (ToCs) and corresponding interventions. Regardless of the context, transformational leadership employs a co-creative process to thoroughly understand the problem, its underlying conditions, assumptions, and the desired change goals or outcomes. From this, leaders work backwards, identifying long-term, medium-term, and short-term outcomes or preconditions necessary for success, with measurable indicators to track progress. These outcomes determine the necessary intervention actions, resources, and measurable outcomes. Leveraging these ToC principles and Reinholz and Andrews' (2020) logic model, Figure 2 illustrates a multilevel, synchronised ToC Transformation Change Pathway (TCP) for building a resilient social sector and achieving national SD. (Stein & Valters, 2012; Abercrombie et al., 2018; Arensman et al., 2018).

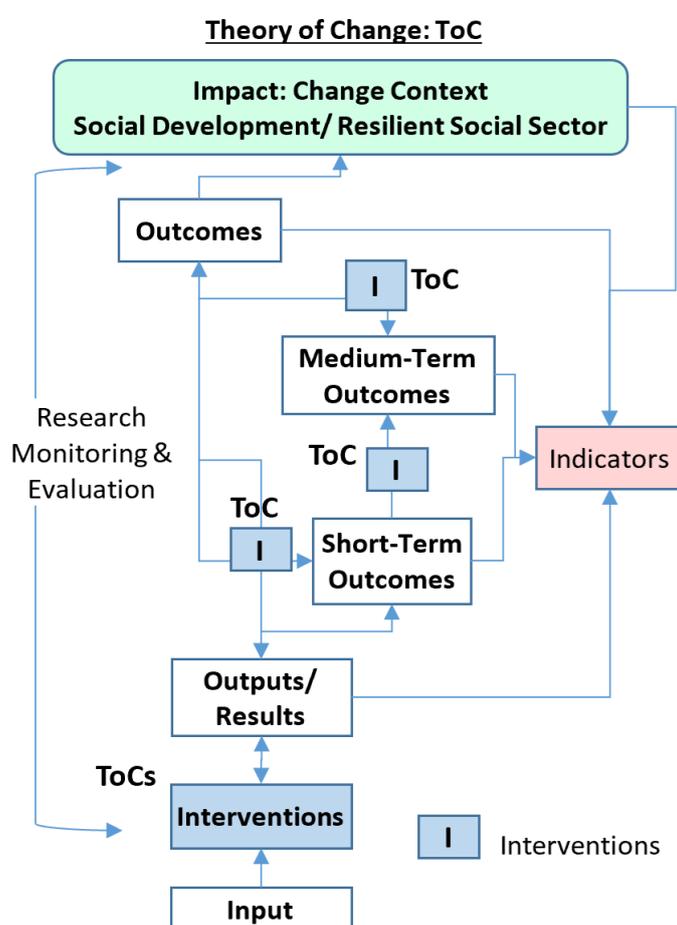


Figure 2: Transformation Change Pathway (TCP). Source: Adapted Model, Reinholz & Andrews (2020). Authors Developed, Sep 2023

Navigating this pathway toward building a resilient social sector and achieving the SDGs' triple bottom line (social, economic, and environmental) requires synchronisation and collaboration among the government, private, and social sectors. This co-creational process is essential. While academic research provides evidence-based guidance for SD, implementing a collaborative approach in the Caribbean context presents challenges, particularly in building trust and managing relationships.

Transformational change in achieving the desired impact of social sector resilience and Sustainable Development (SD) is complex, requiring multilevel, multi-contextual changes with each process of entrepreneurial action for transformational change customised to the context and achieved through interlinked or

interdependent Transformational Change (ToCs) and associated intervention actions. Irrespective of the contextual level, transformational leadership employs a co-creative process to gain a comprehensive understanding of the contextual problem, situational context, underlying conditions and assumptions, and a definition of the desired change goal (s) or outcome/impact. With that end goal, one works backwards, identifying the long-term and associated medium- and short-term outcomes or preconditions for impact success, using quantifiable outcome indicators. Outcomes dictate the required intervention actions, associated input resources, and related measurable outputs. Leveraging these ToC concepts and Reinholz and Andrews's (2020) logic model, Figure 2 demonstrates a multilevel synchronised ToC Transformation Change Pathway [TCP] for building a resilient social sector and national SD. (Stein & Valters 2012; Abercrombie et al, 2018; Arensman et al., 2018).

3.4.2. Social Development - Collaborative/Co-creation Approach

Cross-sectoral collaboration is crucial for building resilience and driving social development (Kolk & Lenfant, 2015; Lane, 2013; Sakarya et al., 2012). By bringing together stakeholders with diverse knowledge and perspectives, collaboration fosters well-informed and innovative solutions, enabling resource sharing and reducing costs, risks, and uncertainties (Sørensen, 2012; Sdunzik et al., 2022). However, despite the many benefits, cross-sector collaboration faces several challenges; the first is recognising the need for collaboration. Once formed, managing relationships involves navigating issues of trust, cultural norms, authority, policies, and conflicting goals, interests, and priorities (Gardner, 2005; Crosby & Bryson, 2005; Babiak & Thibault, 2009; Di Domenico et al., 2009). For effective collaboration within the ToC/TCP framework, it is essential to understand and synthesise diverse stakeholder perspectives, biases, values, expectations, and assumptions. This ensures the development, integration, and implementation of multifaceted solutions that go beyond the vision of any single sector or stakeholder (Agustin et al., 2016; Gardner, 2005).

To facilitate effective collaboration, Sdunzik et al. (2022) identified key relationship enablers for each stage of the change process, with monitoring, management, and measurement indicators to ensure alignment and success (see Table 2). The stages include:

Stage 1 – Collaboration/Partnership Formation

Stage 2A – Operations/Implementation of Strategies/Actions

Stage 2B – Monitoring of SD Actions/Maintenance of Collaborative Efforts

Table 2: Collaboration Relationship Management

Relationship Enablers	Definitions	Indicators
Stage 1: Collaboration & Co-creation Formation		
Mutuality	Gains for all partners for shared benefits	Interdependence; Cooperation; Alignment; Synergy; Outcomes
Positionality	Structural and systemic balance/ imbalance between partners	Balance; Influence; Hierarchy; Redistribution; Power
Risk Allocation	Assignment of risks between partners	Reduce; Negotiate; Define; Control; Manage
Roles and Responsibilities	Identification and allocation of tasks within a partnership	Activities; Targets; Funds; Involvement; Exchange
Shared Authority and Decision-making	Shared and integrative leadership and representation	Decentralization; Coherence; Consistency; Participation; Inclusion
Stage 2A: Operations/Implementations of SD Strategies		
Communication	Conveyance of information in an open, regular, accurate manner	Negotiate; Identify; Align; Problem-solving; Check-in

Flexibility and Compromise	Willingness to accommodate emerging needs and trends	Balance; Negotiate; Conflict handling; Responsiveness
Managerial Efforts	Alignment and coordination of partnering activities and processes	Adjustment; Optimization; Coordination; Performance management
Performance Enhancing Strategies	Procedural and processual mechanisms to support partnership activities	Boundary spanning; Interaction; Integration; Learning; Coordination

Stage 2B: Monitoring of SD actions/ Maintenance of Collaborative Efforts

Accountability	Assurance of partnership goal pursuit despite individual interests	Reporting standards; Enforceability; Answerability; Bidirectionality
Commitment	Investment of time and resources and willingness to engage	Dedication; Resource allocation; Long-term involvement; Buy-in
Transparency	Degree of disclosure of intentions, process, and progress	Honesty; Candor; Assurance; Joint Learning
Trust	Assurance of obligation to expectations and insurance against corresponding shortcomings	Benevolence; Competence; Credibility; Integrity; Deterrence

Source: Sdunzik J, Bampoh D, Sinfield J, McDavid L, Burgess D, Burgess W (2022); An Interdisciplinary Perspective on Private Sector Engagement in Cross-Sector Partnerships: The Why, Where, and How

Each step of this collaborative and co-creative approach, with supportive relationship enablers, provides transparency of actions, thereby winning legitimacy for SD actions. A detailed description of each relationship enabler is beyond the scope of this paper. However, there is the expectation of customisation to reflect the ToC context.

Having addressed the anticipated startup and transitional challenges associated with transformational change (Figure 2) and the formation and relationship management challenges at each stage of the change process (Table 2), the following section introduces the first known national/sectoral Transformational Theory of Change (ToC).

3.5 Transformational Theory of Change – Resilient Social Sector

This section presents a Transformational Theory of Change (TToC), shown in Figure 3, to build absorptive, adaptive, and transformative resilience within the social sector and simultaneously addresses how a co-creational approach between the social, business, and governmental sectors can meet the SDGs while pursuing SD.

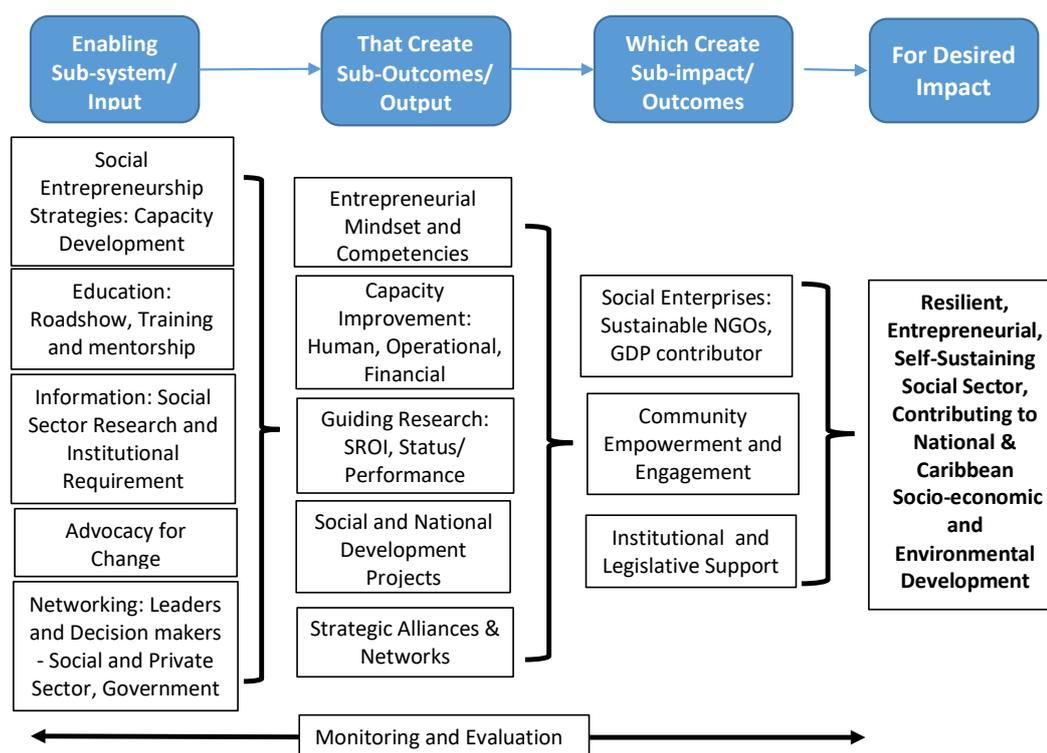


Figure 3: Transformational Theory of Change [TToC]

Source Social Enterprise and Entrepreneurship Development Steering (SEEDS) Committee, (2023)

The change context is the Caribbean Region's SD and social sector resilience, with the transformational change or social impact being: *"Resilient, Entrepreneurial, Self-Sustaining Social Sector, Contributing to National & Caribbean Socioeconomic and Environmental Development"*.

The TToC critical assumptions are (1) acceptance of SE concepts and collective functional SE (Zivkovic, 2011) as drivers for building social sector resilience and SD transformational change, (2) business, social and public entrepreneurs are the SD transformational leaders (3) active participation and collaboration from government, private, and social sectors, and (4) a collaborative and co-creational approach in the transformational process, with a core leadership team and a network of cross-sectoral and sector-specific groups, including academia for monitoring and evaluation evidence-based research.

3.5.1. The Transformational Process

Baseline studies on the Caribbean social sector, such as those by Medine and Minto-Coy (2023) on SE strategies and social enterprises, serve as a foundation for this strategic intervention, providing input on SSO's use of SE strategies, their performance (operational, financial, and social), and institutional support and gaps. Those datasets and best practices information on SE and its application for SSOs' sustainability guide change interventions and assist in determining monitoring and evaluation indicators (Bamberger, 2010).

The Enabling Subsystems address Caribbean collaboration limitations, building sectoral and societal support for the desired impact. Leveraging and sharing best practices in SE and SD through informal (e.g., roadshows) and formal (conferences, workshops, and training) channels builds awareness and sectoral leadership support. These forums identify sector-specific issues, the desired impact of change, and the required interventions, while fostering networks and partnerships for intervention efforts. Operationalising the change context to achieve short-term, medium-term, and long-term outcomes involves identifying context-specific assumptions, required interventions, resource needs, expected outputs, and performance indicators. Systematic collaboration, coordination, management strategies, and accountability and assurance measures ensure stakeholder transparency and coordination. Continuous monitoring, evidence-based research, and situational learning enable the updating and realignment of indicators, informing intervention adjustments, building trust, and ensuring alignment with the SD vision (see Figure 2 and Table 2).

3.6. Model Limitations

The TToC assumptions for a co-creational/collaborative approach are also the limitations. While Stage 1 of Table 2 addresses formation challenges, a significant challenge in the Caribbean context is the apparent unwillingness of governmental and private sectors to genuinely collaborate with SSOs, negatively impacting the posited TToC. This is a major limitation, especially since the model highlights the need for institutional support and multisectoral networks as key enabling inputs to the TToC.

While ToC concepts are not new, this is the first known TToC model at a national level within the context of the Caribbean and developing countries, and thus, it should be tested. Considering the collaboration limitations, testing would be conducted at level 1 of the TCP (Figure 2), simultaneously testing that model and feeding it into the "Advocacy" sub-input of the TToC to build multisectoral support. This includes verifying the applicability of the "borrowed" Collaboration Relationship Enablers (Table 2)

Notwithstanding, what remains clear is the timeliness and relevance of the TToC model for the Caribbean and wider Latin American and other developing contexts contending with similar resilience-building and SD challenges. The contextual nature of the TToC allows for its application at organisational and sectoral levels.

4. Future Implications for Policy and Practice

International experiences, reinforced by UN Resolution A/77/L.60, confirmed the transformative potential of SE and a social enterprise with a co-creative/collaborative approach in driving SD and realising the SDGs, supporting the TToC conceptual principles. In the context of the Caribbean and other developing countries. The successful transition of traditional SSOs into social enterprises requires comprehensive changes in institutional support encompassing financial options, capacity-building training, research, knowledge transfer, and supportive legal and regulatory frameworks.

However, genuine collaboration and collective actions between social, business, and governmental sectors with such supportive systems are relatively absent in the Caribbean context, reinforcing the relevance of the TToC conceptual principle for multisectoral management leadership and co-creation action needed for SD.

4.1 Multisectoral/Co-creational Actions

The successful transition of traditional SSOs into social enterprises is a multisectoral collaborative effort with a supportive institutional environment. However, most such support systems are lacking in the Caribbean and other developing countries. The TToC advocated collaboration between the social, business, and governmental sectors to address all sectoral interests. Such collaborative efforts, with resultant co-creative actions, ensure relevant interventions aligned with the SD agenda.

However, acknowledging potential limitations in collaboration and co-creation, we introduce the multilevel TCP with accountability measures. This will guide interventions at an organisational, sectoral, and national level, assuring a whole-system synchronisation approach toward SD. The CRE addresses potential and anticipated cross-sectoral and co-creational collaboration issues. Both the TCP and CRE serve as foundational support for pioneering our national-level TToC.

4.2 Managerial Implications

The successful transition of traditional SSOs into social enterprises requires entrepreneurial managers with some business management training or experience. These entrepreneurial SSO managers leverage business-like and earned income strategies, resulting in SSO operational and financial sustainability as they address their social mission with the necessary operational capability to tackle pressing societal issues and contribute to national Sustainable Development (SD).

Most Caribbean SSOs operate like traditional NPOs with financial donor dependencies, often managed by people with a passion for social change but not necessarily management skills. The successful transition of traditional SSOs into social enterprises requires managers with some management training or experience, as SSOs must operate as social enterprises and achieve dual financial and social sustainability objectives. However, the necessary institutional support, encompassing capacity-building training, financial options beyond donations, and supportive legal and regulatory frameworks, is often lacking in the Caribbean and developing countries contexts.

Comprehensive changes to institutional support and genuine collaborative and collective actions between the social, business, and governmental sectors are necessary prerequisites for realising the SDGs and achieving SD. The importance of the TToC-advocated multisectoral collaboration and coreational efforts needed for SD is emphasised, reiterating the call for multisectoral management leadership and co-creation action.

5. Conclusions

Supported by empirical evidence from developed and developing countries, this paper proposes the TToC and the transformational power of SE, with multisectoral and co-creative efforts, as viable developmental alternatives for building social sector resilience, leading to national and Caribbean Sustainable Development (SD). The core theoretical contribution of this study lies in the introduction of the TToC. The multilevel use of the ToC concepts, typically used at the social programmes level, to synchronised applications at the organisation, sectoral, and national levels, with communication and collaboration strategies facilitating that synchronisation, and the marriage of conceptual principles associated with the developing field of SE, applied in the developing Caribbean countries context, which suffers from a lack of pertinent research information, simultaneously introduce new conceptual principles into the literature and bridge that research gap. Future research will provide proof of concept and opportunities to bridge current research gaps. Furthermore, such an amalgamation of conceptual principles that outline a pathway and mechanism capable of driving systemic change for sustainable development, particularly in contexts marked by entrenched social and environmental challenges, offers a lens for future research that explores the role of SE in sustainable development.

By embracing our TToC conceptual principles, we can overcome the limitations of single-sector efforts and pave the way for sustainable socioeconomic progress. This will prompt a long-overdue conversation on best practices for collaborative social and environmental development, as well as national and Caribbean sustainability. Academic researchers and decision-makers from governmental organisations, civil society, and the business sector must come together to foster multisectoral collaboration and the formation of Transformational Leadership teams. These efforts can lay the groundwork for collective functional SE and transformational entrepreneurship, which are the foundational principles of our TToC.

The advocated multisectoral collaborative relationships can result in enhanced business models, improved logistics for SSOs, and a more favourable public image and reputation for businesses. Shared best practices and multisectoral alliances hold the promise of identifying innovative SD projects at organisational and national levels, effectively addressing national and regional social development. Sharing stories of transition and intervention can elevate sector awareness and garner vital support.

However, it is essential to recognise that any change process is inherently multifaceted. It hinges on shared information and tangible stakeholder value, driving behaviour and action within all sectors. Therefore, we recommend developing a comprehensive data instrument to capture the performance of SSOs. This would enable the determination of their operational, financial, and social outcomes, both pre- and post-interventions, facilitating evidence-based reporting and accountability.

Ultimately, our research underscored the potential for a transformative path in the Caribbean through sustainable energy (SE) and collaborative strategies. These findings provide a roadmap for addressing the Region's socioeconomic and environmental challenges. By embracing the power of SE and fostering multisectoral collaboration, we can work collectively toward sustainable development and the realisation of SDGs, surmounting limitations and forging a more resilient and sustainable future for the Caribbean and beyond. Ultimately, the conceptual TToC model is relevant for all economies where similar SD challenges exist and requires testing in the Caribbean, the wider Latin American Region, and beyond, where similar developmental challenges persist.

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Article

Strategic sustainability: ESG's role in shaping credit ratings in global banking and its impact on profitability and efficiency

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Abstract: This study examines the impact of Environmental, Social, and Governance (ESG) performance on the credit ratings, profitability, and operational efficiency of the world's largest banks. Using an explanatory sequential mixed-methods design, the research integrates quantitative analysis via Partial Least Squares Structural Equation Modeling (PLS-SEM) with qualitative content analysis of sustainability and annual reports from selected banks. The study explores the direct and moderating effects of ESG on asset turnover (AT), earnings before interest and taxes (EBIT), and credit ratings. Results show that ESG performance significantly improves credit ratings but negatively affects EBIT, indicating short-term profitability trade-offs. AT positively influences credit ratings, though reverse coding suggests a nuanced interpretation. ESG also moderates the AT–credit rating relationship, implying that high ESG performance may reduce the marginal benefit of operational efficiency on creditworthiness. However, ESG does not significantly moderate the EBIT–credit rating link. These findings highlight the complex role of ESG in financial evaluations and underscore the need for strategic alignment between sustainability initiatives and financial performance. The study advocates integrating ESG metrics into credit risk models and refining profitability indicators to account for ESG-related externalities, positioning ESG as a strategic lever to enhance institutional credibility and long-term resilience.

Keywords: credit ratings, ESG performance, global banking, profitability and efficiency, sustainability and risk assessment

1. Introduction

In the contemporary global economy, banks are not merely financial intermediaries; they are systemic institutions that influence capital allocation, economic development, and financial stability across borders. As the backbone of the financial system, global banks facilitate investment, manage risk, and support growth in both the public and private sectors. Their scale and interconnectedness mean that their operational decisions – particularly those related to risk management and sustainability – have far-reaching implications for markets and societies alike (Carè & Weber, 2023).

The importance of studying the relationship between ESG performance and credit ratings lies in the growing demand for transparency and accountability in financial markets. Credit ratings serve as a key signal of a bank's financial health and risk profile, influencing its access to capital and cost of borrowing. If ESG performance is indeed a determinant of creditworthiness, then it becomes a strategic lever for banks seeking to enhance their financial standing and stakeholder trust. Moreover, understanding whether ESG moderates the effects of

traditional financial metrics – such as profitability (measured by EBIT) and operational efficiency (measured by asset turnover) – can offer deeper insights into how sustainability integrates with core financial performance.

Despite its growing importance, empirical research on the impact of ESG on credit ratings and its moderating effects on financial indicators remains limited – particularly in the context of global banking. This study addresses that gap by examining whether ESG performance directly influences credit ratings and whether it amplifies or attenuates the impact of profitability and efficiency on creditworthiness. By doing so, it contributes to a more integrated understanding of how sustainability and financial performance intersect in shaping the risk profiles of the world's largest banks.

1.1 Statement of the Problem

This study answers the question: To what extent does ESG performance, along with financial indicators such as asset turnover and EBIT, influence the credit ratings of the world's largest banks, and how do interaction effects between ESG and financial indicators moderate this relationship?

1.2 Objectives of the Study

Specifically, this study aimed to:

1. Determine the causal effect of ESG performance on the credit ratings of global banks.
2. Assess the direct impact of financial indicators – specifically asset turnover and earnings before interest and taxes – on credit ratings.
3. Evaluate whether ESG performance moderates the relationship between asset turnover and credit rating.
4. Evaluate whether ESG performance moderates the relationship between EBIT and credit rating.
5. Analyze the effect of ESG performance on operational efficiency and profitability.
6. Identify the extent to which ESG performance, alone or in combination with financial indicators, explains the variance in credit ratings.
7. Contribute to theoretical advancement by demonstrating how seven foundational frameworks collectively explain the interplay between sustainability and credit risk.

2. Literature Review and Hypotheses Development

The literature review focused on empirical and theoretical insights on three key dimensions: (a) the direct impact of ESG performance on credit ratings, (b) the influence of ESG on financial indicators such as asset turnover (AT) and earnings before interest and taxes (EBIT), and (c) the moderating role of ESG in shaping the relationship between these financial indicators and credit ratings.

2.1 ESG and Credit Ratings

ESG factors are considered non-financial performance indicators and are used to identify issues related to business ethics, corporate social responsibility, and corporate governance (Kim & Li, 2021). The growing body of literature examining the relationship between ESG performance and credit ratings reveals a consistent and increasingly robust link, particularly when ESG is measured as a composite score. Studies such as Agosto et al. (2023), Kim and Li (2021), Devalle et al. (2023), and Zanin (2021) provide compelling evidence that overall ESG scores are statistically significant predictors of credit ratings, even after controlling for financial indicators. Devalle et al. (2023) found that ESG scores positively influence long-term issuer credit ratings, with U.S. firms exhibiting greater significance of the broader ESG theme than European counterparts. Zanin (2021) confirmed that the aggregate ESG score significantly improves model fit across sectors and agencies, reinforcing the idea that ESG performance is increasingly factored into creditworthiness assessments. Agosto et al. (2023) further advanced this understanding by developing a Bayesian model that combines ESG scores from multiple providers, demonstrating improved predictive accuracy for credit rating classifications, especially for highly rated firms.

Some studies (Agosto et al., 2023; Devalle et al., 2023; Hentilä, 2022; Kim & Li, 2021; Kousa, 2023; Vaivos, 2022) collected data for publicly listed companies in the US, Europe, and Asia, spanning the period of three to 20 years in various industries within the financial year 1990 to 2020. Vaivos (2022) observed that companies with higher ESG scores were assigned higher credit ratings, indicating lower credit risk and easier access to debt financing. Agosto et al. (2023) found that the combined ESG scores were effective in predicting companies' credit ratings. This study suggested that a combined ESG rating was better at identifying the most creditworthy companies, with credit rating-class prediction accuracy higher than that obtained from a single ESG metric.

In contrast, studies focusing on individual ESG pillars yield more nuanced, and sometimes conflicting, findings. For instance, while Zanin (2021) and Chodnicka-Jaworska (2021, 2022) emphasize the Environmental pillar as the most influential, particularly in environmentally sensitive sectors like energy and mining, other studies, such as Devalle et al. (2017) and Kim and Li (2021), highlight the Social and Governance pillars as more impactful. Vaios (2022) and Brogi et al. (2022) also found that the social pillar was the most significant across regions and sectors. These discrepancies suggest that, while overall ESG scores offer a reliable signal of creditworthiness, the relevance of individual ESG dimensions may vary across sectors, regional regulatory environments, and credit rating agency methodologies. Therefore, while the integration of ESG into credit risk models is gaining traction, a one-size-fits-all approach may overlook important contextual differences in how ESG factors influence credit assessments.

H1: ESG performance improves Credit Ratings.

2.2 ESG and Asset Turnover (Efficiency)

ESG performance has increasingly been linked to operational efficiency, often captured by asset turnover (AT). Firms with strong ESG practices tend to adopt resource-efficient processes, optimize asset utilization, and implement sustainability-driven operational strategies, all of which can enhance AT (Kim & Li, 2021; Michalski & Low, 2021). ESG engagement not only improves a firm's reputation and stakeholder trust but also contributes to financial resilience by reducing operational risks and improving efficiency (Wu, 2023). Moreover, ESG performance serves as reputational insurance during periods of financial distress, thereby indirectly supporting operational stability and efficiency (Chodnicka-Jaworska, 2021; Devalle et al., 2023). These dynamics suggest that ESG initiatives, while primarily aimed at sustainability, can also yield operational benefits that strengthen a firm's ability to generate revenue from its asset base, thereby influencing creditworthiness through improved AT.

H2: ESG performance improves asset turnover.

2.3 ESG and Earnings before Interest and Taxes (Profitability)

Earnings Before Interest and Taxes (EBIT) is a key profitability measure, and its relationship with ESG performance is complex. While ESG initiatives can enhance long-term value creation, they often involve upfront costs that may temporarily reduce EBIT (Bonacorsi et al., 2022). However, ESG performance is increasingly recognized as a strategic asset that enhances long-term financial stability and creditworthiness by reducing default risk and improving access to capital (Aslan et al., 2021; Agosto et al., 2023). Henkel et al. (2024) introduced the Sustainable Performance Accounting (SPA) framework, which adjusts traditional EBIT to account for ESG-related externalities by defining Sustainable EBIT (SEBIT). This approach treats ESG costs (e.g., emissions) as provisions and ESG benefits (e.g., carbon sequestration) as assets, providing a more accurate representation of operational performance. Although conventional EBIT may understate the economic impact of sustainability investments, SEBIT demonstrates that ESG engagement can ultimately improve profitability when sustainability impacts are internalized. Thus, when properly integrated into financial metrics, ESG performance reinforces its materiality and its role in driving sustainable profitability (Henkel et al., 2024).

H3: ESG performance improves earnings before interest and taxes.

2.4 Asset Turnover on Credit Ratings

Asset turnover (AT), as a measure of operational efficiency, remains a significant predictor of credit ratings in traditional and ESG-integrated models. Studies confirm that AT and related efficiency ratios are consistently included in credit risk models, alongside leverage and liquidity indicators (Chodnicka-Jaworska, 2021; Devalle et al., 2023). Higher AT generally signals effective resource utilization, which credit rating agencies interpret as a sign of financial stability and lower default risk (Michalski & Low, 2021). While ESG factors are gaining prominence, research shows that operational efficiency metrics, such as AT, continue to play a critical role in explaining creditworthiness, particularly when combined with other financial indicators (Billio & Giacomelli, 2022; Agosto et al., 2023). These findings underscore that AT remains a core component of credit rating methodologies, reflecting its importance in assessing a firm's ability to generate revenue from its asset base.

H4: Asset turnover improves Credit Rating.

2.5 Earnings before Interest and Taxes on Credit Ratings

Earnings Before Interest and Taxes (EBIT) is widely recognized as a fundamental measure of profitability and a key determinant of credit ratings. Multiple studies confirm that EBIT and related profitability ratios, such as EBIT/Total Revenue and EBITDA, significantly influence credit risk assessments (Brogi et al., 2022; Devalle et al., 2017). Higher EBIT indicates stronger operating performance and debt-servicing capacity, which rating agencies associate with lower credit risk (Kim & Li, 2021; Michalski & Low, 2021). However, some research notes that EBIT's explanatory power may vary across contexts, with liquidity and leverage sometimes exerting stronger effects (Kousa, 2023). Despite these variations, EBIT remains integral to credit rating models, often serving as a primary indicator of financial health and resilience, even when ESG factors are incorporated (Billio & Giacomelli, 2022; Bonacorsi et al., 2022).

H5: EBIT improves Credit Rating.

2.6 Moderation Role of ESG on the Relationship Between Asset Turnover and Credit Ratings

Several studies suggest that ESG performance can moderate the impact of operational efficiency, measured by asset turnover (AT), on credit ratings. ESG mitigates risk by reducing information asymmetry and perceived risk, thereby amplifying the positive effect of strong operational efficiency on creditworthiness (Cubas-Díaz & Sedano, 2018; Devalle et al., 2017). Chodnicka-Jaworska (2021) provides evidence that ESG factors can offset negative financial signals, such as high leverage, and enhance the explanatory power of efficiency metrics in credit rating models. Similarly, Agosto et al. (2023) demonstrate that firms with weaker financial fundamentals, but strong ESG performance, can still achieve favorable credit ratings, indicating that ESG can compensate for deficiencies in operational indicators. Kousa (2023) further supports this by showing that ESG scores remain significant even when controlling for financial ratios, suggesting that ESG strengthens the predictive relationship between AT and credit ratings, particularly in sectors where sustainability is material.

H6: ESG moderates the relationship between AT and Credit Rating.

2.7 Moderation Role of ESG on the Relationship Between EBIT and Credit Ratings

The moderating role of ESG on the relationship between profitability, measured by EBIT, and credit ratings is well documented in the recent literature. ESG performance can buffer the adverse effects of low profitability, allowing firms with weaker EBIT to maintain stronger credit ratings when sustainability practices are robust (Chodnicka-Jaworska, 2021; Hentilä, 2022). Agosto et al. (2023) confirm that ESG scores improve the accuracy of credit risk assessments by mitigating the effects of poor financial performance, particularly for speculative-grade firms. However, the strength of this moderation varies across contexts; for example, Kim and Li (2021) note that ESG-profitability interactions are stronger in large firms with stronger governance structures. Bonacorsi et al. (2022) also highlight that ESG's moderating effect is context-dependent, influenced by sectoral and regional factors. Overall, these findings indicate that ESG integration not only enhances the explanatory power of EBIT in credit rating models but also provides a strategic buffer against profitability-related risks.

H7: ESG moderates the relationship between EBIT and Credit Rating.

2.8 Research Gap

While numerous studies have examined the individual effects of ESG performance, financial efficiency, and profitability on credit ratings, there remains a lack of integrated analysis of their joint and interactive impacts, particularly within the global banking sector. Most existing literature focuses on either ESG or financial indicators in isolation, often within specific regions or industries. Furthermore, the moderating role of ESG in the relationship between financial performance and creditworthiness remains underexplored, particularly through quantitative models that capture interaction effects.

Table 1. Research gaps

Authors	Variables Studied	Contextual Gaps			
		Demographic	Temporal	Geographic	Methodological
Devalle et al. (2017)	ESG, Credit Ratings	Yes	Yes	Yes	Yes
Cubas-Díaz & Sedano (2018).	Sustainability performance, Credit Ratings	Yes	Yes	No	Yes
Jang et al. (2020)	ESG scores, Bond Returns	Yes	Yes	Yes	Yes
Aslan et al. (2021)	ESG scores, credit default probabilities	Yes	Yes	Yes	Yes
Chodnicka-Jaworska (2021)	ESG, financial ratios, Credit Ratings	Yes	Yes	Yes	Yes
Michalski & Low (2021)	ESG, financial ratios	Yes	Yes	No	Yes
Kim & Li (2021)	ESG, ROA, Credit Ratings	Yes	Yes	No	Yes
Zanin (2021)	ESG, Credit rating	Yes	Yes	Yes	Yes
Kim & Kim (2022)	Environmental Risk (GHG emissions, energy use), Credit Ratings, Market Competition (HHI)	Yes	Yes	Yes	Yes
Brogi et al. (2022)	ESG, Altman Z-score, PD	Yes	Yes	No	Yes
Chodnicka-Jaworska (2022)	ESG, financial ratios, Credit Ratings	Yes	Yes	Yes	Yes
Billio & Giacomelli (2022)	ESG, Financial performance (Revenue, Opex, Capex, debt structure), Credit rating, Probability of default	Yes	Yes	Yes	Yes
Bonacorsi et al. (2022)	ESG, Altman Z-score, accounting ratios	Yes	Yes	Yes	Yes
Vaios (2022)	ESG ratings, Credit Ratings	Yes	Yes	No	Yes
Hentilä (2022)	ESG, Credit Ratings, Financial Controls	Yes	Yes	Yes	Yes
Agosto et al. (2023)	ESG, Credit Ratings, Financial Ratios	Yes	Yes	Yes	Yes
Agosto et al. (2023)	ESG, credit ratings, and financial ratios	Yes	Yes	Yes	Yes
Agosto et al. (2023)	ESG, Credit ratings	Yes	Yes	Yes	Yes
Kousa (2023)	ESG, credit ratings, EBIT margin, current ratio, equity ratio, industry, revenue	Yes	Yes	Yes	Yes

Wu (2023)	ESG, trade credit financing (accounts payable/total assets)	Yes	Yes	Yes	Yes
Devalle et al. (2023)	ESG, credit ratings	Yes	Yes	Yes	Yes

Source: Compiled by Author

2.9 Multi-theoretical Framework

A critical observation from the literature reviewed is the absence of explicit theoretical or conceptual frameworks guiding empirical investigations into the relationship between ESG performance and credit risk. Hence, this study is grounded in a multi-theoretical framework that integrates sustainability, strategic management, and financial signaling perspectives to explain the joint and moderating effects of ESG performance, asset turnover (AT), and earnings before interest and taxes (EBIT) on credit ratings in the global banking sector.

- Triple Bottom Line (Elkington, 1994). The overarching framework is the Triple Bottom Line (TBL), which posits that firms should simultaneously pursue environmental, social, and economic goals. ESG performance reflects this multidimensional approach to value creation. In this study, ESG is conceptualized as a composite construct encompassing environmental, social, and governance dimensions, which collectively influence both financial performance and creditworthiness.
- Stakeholder Theory (Freeman, 1984) and Legitimacy Theory (Suchman, 1995). These theories support the role of ESG in managing stakeholder relationships and maintaining societal legitimacy. Banks that perform well on ESG dimensions are more likely to gain trust from regulators, investors, and the public, which can translate into improved credit ratings. These theories justify the hypothesized direct effect of ESG on credit ratings.
- Resource-Based View (Barney, 1991). The Resource-Based View (RBV) suggests that ESG capabilities – such as sustainable operations, ethical governance, and social responsibility – can be strategic resources that enhance operational efficiency (AT) and profitability (EBIT). This supports the hypothesized paths from ESG to AT and EBIT.
- Sustainable Performance Accounting (Henkel et al., 2024). This modern accounting framework, as discussed in Section 2.2, introduces Sustainable EBIT, which adjusts traditional EBIT to account for ESG-related externalities. It reinforces the idea that ESG investments, while potentially costly in the short term, contribute to long-term financial resilience and should be integrated into profitability assessments.
- Signaling Theory (Spence, 1973). Signaling theory underpins ESG's role as a signal of reduced risk and enhanced transparency. ESG disclosures can reduce information asymmetry between banks and credit rating agencies, thereby influencing credit ratings directly and moderating the effects of financial indicators. This supports the inclusion of interaction terms (ESG × AT and ESG × EBIT) in the model.
- ESG (UN, 2004). UN outlines the critical context for understanding the strategic integration of ESG into financial decision-making. In its report, the UN called on major financial institutions to incorporate ESG factors into asset management, securities brokerage, and research processes. It emphasized that ESG considerations are not merely ethical imperatives but are material to long-term financial performance and risk management. The report catalyzed the mainstreaming of ESG in investment analysis and laid the groundwork for subsequent regulatory and institutional shifts. Its influence is evident in the evolving methodologies of credit rating agencies, which increasingly factor ESG metrics into their assessments.

Figure 1 presents a multi-theoretical framework and provides a robust theoretical basis for examining how ESG and financial indicators jointly shape credit ratings in the banking sector, in line with Creswell and Creswell (2023, pp. 51–78). The authors emphasize that when a single theory is insufficient to explain a multifaceted phenomenon, researchers should integrate multiple theoretical perspectives to enhance explanatory depth and analytical rigor.

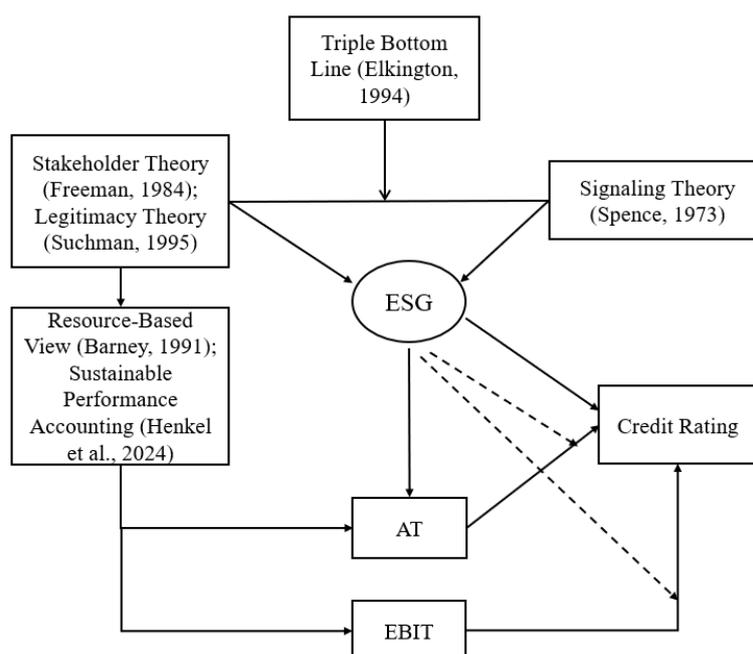


Figure 1. Multi-theoretical Framework.

Source: Triple Bottom Line (Elkington, 1994), Stakeholder Theory (Freeman, 1984), Legitimacy Theory (Suchman, 1995), the Resource-Based View (Barney, 1991), Sustainable Performance Accounting (Henkel et al., 2024), Signaling Theory (Spence, 1973) and ESG (UN, 2004)

3. Materials and Methods

3.1 Research Design

This study employed a cross-sectional research approach and used an explanatory sequential mixed-methods design, in which results were first analyzed quantitatively and then further explained and deepened through qualitative research (Creswell & Creswell, 2023). The research utilized secondary data and applied PLS-SEM to test the hypothesized relationships.

3.2 Sample and Data Sources

The initial sample was drawn from the top 100 banks ranked by S&P; however, 5 banks were excluded due to incomplete data, resulting in a final sample of 95 banks. This represents a 95% usable rate, which meets the minimum sample size threshold recommended for PLS-SEM (Hair et al., 2022). The data pertains to the fiscal year 2024 to ensure consistency in ESG evaluation and financial reporting.

Table 2. Summary profile of selected banks by continent

Continent	Countries Represented	No. of banks	Mean scores/rating					
			E	S	G	AT	EBIT	CR
Asia	China, Japan, India, Qatar, Singapore, South Korea	38	38.53	46.13	45.39	0.0190	\$11.6b	7.21
Australia	Australia	4	69.00	61.00	60.25	0.0180	\$7.19b	4.00
Europe	Austria, Belgium, Denmark, Finland, France, Germany, Italy, Netherlands, Norway, Spain, Sweden,	29	64.86	58.34	60.17	0.0222	\$9.17b	6.03

	Switzerland, United Kingdom							
North America	Canada, United States	21	43.14	44.00	49.00	0.0350	\$13.23b	6.62
South America	Brazil	3	74.33	89.00	77.67	0.0491	\$7.75b	11.67
		95						

To complement the quantitative findings of this study, a qualitative content analysis was conducted on the publicly available sustainability and annual reports of two strategically selected banks: Industrial and Commercial Bank of China (ICBC), headquartered in Asia, and Barclays PLC, headquartered in Europe. These banks were selected based on their contrasting profiles in ESG performance, financial indicators, and credit ratings, which offer rich explanatory potential. The selection ensures geographic and regulatory diversity, as both banks operate within distinct regional ESG expectations. All insights are derived from publicly disclosed documents in accordance with ethical research standards.

3.3 Variables: Type and Measurement

Table 3. Variable type and measurements (n=95)

Variable	Type	Operationalization/Measurement	Scale/Coding
Credit Rating (CR)	Dependent	Credit rating converted to numeric: 1 (AAA) to 21 (D) (lower value = better rating)	Ordinal → numeric, reverse-coded in interpretation
ESG Score	Independent/ Moderator	Composite ESG scores	1–100 (higher = better ESG)
Asset Turnover (AT)	Independent	Revenue ÷ Total Assets (operational efficiency)	Continuous ratio
EBIT	Independent	Earnings before interest and taxes (profitability)	USD billions, continuous
ESG × AT	Interaction/ Moderation	Product of ESG and AT indicators (product-indicator approach in PLS-SEM)	Construct formed from product indicators
ESG × EBIT	Interaction/ Moderation	Product of ESG and EBIT indicators (product-indicator approach in PLS-SEM)	Construct formed from product indicators.

3.4 Operational Framework

The operational framework outlines how the conceptual relationships among ESG performance, asset turnover, EBIT, and credit ratings were translated into measurable constructs. It guided the selection of indicators, the development of hypotheses, and the structure of the statistical model.

Figure 2 presents the operational framework used in this study. The structural model was specified to use SmartPLS 4.0, with ESG dimensions modeled as reflective constructs and AT, EBIT, and credit rating treated as single-indicator variables.

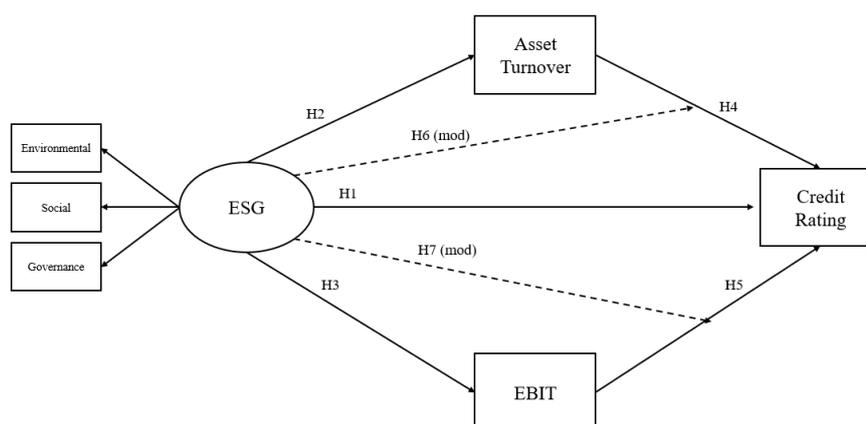


Figure 2. Operational Framework. Source: Author

3.5 Measurement Model and Model Fit

The model demonstrates strong reliability and convergent validity for the constructs used, consistent with established thresholds. The outer loadings for the ESG dimensions – Environmental (0.921), Social (0.941), and Governance (0.946) – exceed the recommended minimum of 0.708, indicating that each indicator is a strong representation of its latent construct (Hair et al., 2022). The composite reliability (CR) and Cronbach's alpha (α) for the ESG construct are 0.955 and 0.930, respectively, both surpassing the 0.70 threshold, which confirms internal consistency (Hair et al., 2019). The average variance extracted (AVE) is 0.876, well above the 0.50 benchmark, supporting convergent validity (Fornell & Larcker, 1981). For single-indicator constructs such as EBIT, Asset Turnover, and Credit Rating, perfect scores (1.0) across all reliability metrics are expected because a single observed variable measures them. These results affirm that the measurement model is statistically sound and suitable for structural equation modeling.

According to Fornell and Larcker (1981), discriminant validity is established when the square root of the average variance extracted (AVE) for each construct (shown on the diagonal) is greater than its correlations with any other construct (off-diagonal values). In the model, the square root of AVE for ESG is 0.935, which exceeds its correlations with Asset Turnover (0.190), EBIT (0.232), and Credit Rating (0.203), indicating good discriminant validity. Similarly, the values for AT (1.000), EBIT (1.000), and CR (1.000) are all higher than their respective inter-construct correlations, which is expected for single-indicator constructs. The results confirm that each construct captures a unique aspect of the model and that multicollinearity is not a concern (Hair et al., 2022). Thus, the measurement model demonstrates strong discriminant validity, supporting the robustness of the structural relationships tested.

3.6 Overall Model Fit

Table 4 presents the model fit indices for both the estimated and saturated models, using three key metrics: the Standardized Root Mean Square Residual (SRMR), the squared Euclidean distance (dULS), and the geodesic distance (dG). The SRMR value for the estimated model is 0.050, which is well below the conservative threshold of 0.08 recommended by Hair et al. (2019), indicating a good fit between the observed and predicted correlations. Similarly, the dULS (0.052) and dG (0.058) values fall comfortably below their respective 99% confidence intervals (HI99), further supporting the model's adequacy. These results suggest that the structural model is well-specified and that the hypothesized relationships among ESG, financial indicators, and credit ratings are consistent with the empirical data. According to Hair et al. (2022), achieving low SRMR, dULS, and dG values is essential in PLS-SEM to confirm that the model is not misspecified. Therefore, the fit indices in Table 4 provide strong evidence of the model's robustness and its suitability for hypothesis testing.

Table 4. Test of model fit.

	Estimated Model		Saturated Model	
	Value	HI99	Value	HI99
SRMR	0.050	0.103	0.041	0.041
d _{ULS}	0.052	0.223	0.036	0.036
d _G	0.058	0.106	0.053	0.069

4. Results

Table 5, presented in this study, reveals considerable variability in ESG scores and financial indicators among the sampled global banks. The environmental performance ($SD=20.057$, $Min=9$, $Max=81$) exhibits a wide range, reflecting divergent approaches to climate strategy and emissions management. This variation is substantiated by the content analysis of ICBC and Barclays' reports. ICBC, while leading in green finance volume, reports high operational emissions due to its industrial exposure and scale. In contrast, Barclays demonstrates a more aggressive decarbonization strategy, including sourcing 100% renewable electricity and substantial investments in climate technologies. Similarly, the dispersion in social performance ($SD = 19.793$; $Min = 16$; $Max = 95$) aligns with regional differences in stakeholder engagement. ICBC emphasizes rural revitalization and pension finance, whereas Barclays focuses on community development, inclusive employment, and digital literacy initiatives. Governance performance ($SD=16.435$, $Min=23$, $Max=91$) exhibits moderate variability, attributable to structural differences in oversight frameworks. ICBC integrates ESG into Party-led governance systems, while Barclays prioritizes board independence, compliance culture, and ESG oversight mechanisms.

Table 5. Descriptive Statistics

	Obs	Mean	Std Dev	Min	Max
Environmental	95	50.000	20.057	9.000	81.000
Social	95	51.368	19.793	16.000	95.000
Governance	95	52.347	16.435	23.000	91.000
EBIT	95	10.916	12.271	-0.481	75.755
Asset Turnover	95	0.024	0.012	0.004	0.057
Credit Rating	95	6.726	2.059	4.000	15.000

The financial indicators further illustrate the heterogeneity of the sample. EBIT values ($SD=12.271$, $Min=-0.481$, $Max=75.755$) indicate substantial differences in profitability. ICBC's scale and state-backed lending model contribute to its high EBIT, while Barclays reports moderate profitability due to strategic investments in ESG and digital transformation. Asset turnover ($SD=0.012$, $Min=0.004$, $Max=0.057$) remains low and relatively stable, reflecting differences in operational models. Barclays' leaner, digitally driven operations yield higher turnover rates compared to ICBC's extensive asset base. Credit ratings are clustered around investment-grade levels ($SD = 2.059$; $Min = 4$; $Max = 15$), yet the reports suggest that ESG performance alone does not determine creditworthiness. Factors such as sovereign backing, governance quality, and strategic alignment play critical roles in shaping credit profiles.

Table 6 reveals important insights into the structural model. Credit Rating, as the primary dependent variable, is moderately explained by the model ($R^2 = 0.315$), with ESG and Asset Turnover contributing small to medium effect sizes, respectively. The interaction between ESG and AT also shows a medium effect, highlighting the importance of moderation in the model. EBIT and $ESG \times EBIT$, however, have negligible effects on Credit Rating, suggesting limited direct or interactive influence. For the other dependent variables, AT and EBIT, ESG accounts for only a small portion of their variance, indicating that ESG alone does not strongly predict operational or profitability metrics. All VIF values are well below the critical threshold of 5, confirming that multicollinearity is not a concern and that the predictors are sufficiently independent for reliable interpretation.

Table 6. Effect Size, Variance Explained, and Inner Collinearity

Endogenous	Exogenous	f ²	Effect	R ²	Strength	VIF
CR	ESG	0.113	Small	0.315	Moderate	1.155
	AT	0.158	Medium			
	EBIT	0.003	Negligible			
	ESG x AT	0.223	Medium			
	ESG x EBIT	0.007	Negligible			
AT	ESG	0.036	Small	0.035	Weak	1.000
EBIT	ESG	0.054	Small	0.051	Weak	1.000

Table 7 presents a negative and significant coefficient for ESG on Credit Rating ($\beta = -0.299$, $t = 3.172$, $p = .002$), indicating that higher ESG performance is associated with better credit ratings. Given that credit ratings are

reverse-coded (1 = highest, 21 = lowest), a negative coefficient indicates a movement toward lower values, i.e., an improvement in creditworthiness. This finding aligns with prior research suggesting that ESG performance enhances institutional credibility and reduces perceived risk (Kim & Li, 2021; Devalle et al., 2023). Similarly, the negative and significant effect of ESG on EBIT ($\beta = -0.227$, $t = 2.615$, $p = .009$) suggests that higher ESG performance may be associated with lower reported profitability, potentially due to the upfront costs of sustainability initiatives. This supports the argument by Henkel et al. (2024) that traditional EBIT may understate the long-term value of ESG investments. Interestingly, AT has a positive and significant effect on Credit Rating ($\beta = 0.344$, $t = 2.920$, $p = .004$). However, because higher numerical values indicate worse credit ratings, this positive coefficient implies that greater operational efficiency is associated with weaker credit ratings – an unexpected result. This may indicate that banks with higher AT ratios pursue more aggressive asset utilization strategies, which rating agencies may perceive as riskier. In contrast, ESG does not significantly influence AT ($\beta = 0.187$, $t = 1.697$, $p = .090$), and EBIT does not significantly affect Credit Rating ($\beta = -0.074$, $t = 0.530$, $p = .596$), suggesting that these paths are not statistically significant. Overall, the results support hypotheses H1, H3, and H4, while H2 and H5 are not supported.

Table 7. PLS Path Coefficients and Moderation Analysis

Hypothesis	Path	β	M	SD	t	p
H1 (Significant)	ESG -> CR	-0.299	-0.292	0.094	3.172	0.002
H2 (Not significant)	ESG -> AT	0.187	0.189	0.110	1.697	0.090
H3 (Significant)	ESG -> EBIT	-0.227	-0.221	0.087	2.615	0.009
H4 (Significant)	AT -> CR	0.344	0.336	0.118	2.920	0.004
H5 (Not significant)	EBIT -> CR	-0.074	-0.051	0.139	0.530	0.596
H6 (Significant)	ESG x AT -> CR	0.370	0.375	0.087	4.230	0.000
H7 (Not significant)	ESG x EBIT -> CR	0.104	0.121	0.128	0.811	0.418

The path analysis results reveal nuanced relationships among ESG performance, financial indicators, and credit ratings, further illuminated by qualitative insights from the sustainability and annual reports of ICBC and Barclays. The significant negative path between ESG scores and credit ratings (reverse-coded) suggests that stronger ESG performance is associated with better creditworthiness. This finding aligns with the strategic framing observed in both banks' disclosures, where ESG is positioned as a tool for risk mitigation and reputational enhancement. Barclays emphasizes ESG integration into governance and stakeholder engagement, while ICBC embeds ESG into its enterprise risk management system. Although this result is consistent with several studies (e.g., Brogi et al., 2022; Michalski & Low, 2021), it contrasts with findings from Kim & Li (2021), who report a negative impact of environmental scores on credit ratings, suggesting that ESG effects may vary by pillar and context.

The non-significant path between ESG and asset turnover supports the notion that ESG initiatives, while strategically important, may not directly enhance operational efficiency. This is reflected in ICBC's emphasis on green finance and inclusive lending, which are long-term strategic investments rather than drivers of short-term asset productivity. The literature offers limited direct evidence on this relationship. However, asset turnover is often treated as a control variable (e.g., Chodnicka-Jaworska, 2021), thereby reinforcing the interpretation that ESG's influence on efficiency is at best indirect.

The significant negative path from ESG to EBIT further supports the trade-off hypothesis, whereby ESG investments—such as compliance, innovation, and sustainability reporting—may reduce short-term profitability. This is evident in both ICBC and Barclays' reports, which detail substantial resource allocation toward ESG initiatives. This finding is consistent with studies such as Billio & Giacomelli (2022) and Bonacorsi et al. (2022), which highlight the cost implications of ESG integration, particularly in capital expenditure and operational adjustments.

The positive path from asset turnover to credit rating (reverse-coded) suggests that leaner operations may be perceived as riskier by rating agencies, especially when aggressive asset utilization is involved. Barclays' higher turnover reflects its digital banking model, while ICBC's lower turnover aligns with its conservative lending practices. This interpretation adds nuance to the existing literature, which generally supports asset turnover as a positive predictor of creditworthiness (e.g., Devalle et al., 2023) but rarely considers its risk-signaling implications.

The non-significant path from EBIT to credit rating underscores that profitability alone may not be a decisive factor in credit assessments. ICBC's strong EBIT does not necessarily translate to superior ratings, likely due to sovereign backing and systemic factors. Similarly, Barclays' moderate EBIT is offset by its robust ESG

disclosures. This finding aligns with Devalle et al. (2017) and Kousa (2023), who report weak or inconsistent effects of EBIT on credit ratings, suggesting that ESG and governance factors increasingly complement traditional financial metrics in credit risk evaluation.

The interaction between ESG and Asset Turnover has a positive and significant effect on Credit Rating ($\beta = 0.370, t = 4.230, p < .001$). However, since Credit Ratings are reverse-coded (1 = highest, 21 = lowest), a positive coefficient indicates a movement toward lower credit ratings, or worsening creditworthiness. This suggests that while operational efficiency (AT) is generally beneficial, its positive interaction with ESG may paradoxically be associated with weaker credit ratings when ESG performance is high. This counterintuitive result may reflect the complexity of how rating agencies interpret ESG-enhanced efficiency, which they may view as indicative of aggressive growth strategies that carry higher risk (Henkel et al., 2024).

This finding challenges the assumption that ESG always amplifies financial strengths and aligns with the cautionary perspective of Bonacorsi et al. (2022), who noted that ESG-related investments can impose short-term financial burdens. It also suggests that the signaling effect of ESG (Spence, 1973) may not uniformly enhance all financial metrics in the eyes of credit rating agencies.

In contrast, the interaction between ESG and EBIT does not have a significant effect on Credit Rating ($\beta = 0.104, t = 0.811, p = .418$), implying that ESG does not meaningfully moderate the relationship between profitability and credit rating. This supports the argument by Henkel et al. (2024) that traditional EBIT may fail to capture the long-term value of ESG investments, and that Sustainable EBIT (SEBIT) may be a more appropriate metric for evaluating profitability in ESG-integrated models. Hence, the results support hypothesis H6 with caution, given the reverse coding of the dependent variable, but do not support hypothesis H7.

The moderation analysis reveals that ESG performance significantly interacts with asset turnover in predicting credit ratings, but not with EBIT. The significant ESG \times AT interaction suggests that high ESG performance may buffer the influence of operational efficiency on creditworthiness. This is consistent with ICBC's integration of ESG into risk systems and Barclays' emphasis on ESG as a reputational signal, both of which may reduce the marginal value of asset turnover in credit assessments. This finding is supported by studies such as Hentilä (2022) and Bonacorsi et al. (2022), which show that ESG disclosure can moderate the effects of financial indicators on credit ratings. In contrast, the non-significant ESG \times EBIT interaction implies that ESG does not amplify or diminish the effect of short-term profitability on credit ratings. This aligns with the strategic framing of ESG in both banks' reports and with literature suggesting that ESG influences long-term financial stability rather than immediate earnings (e.g., Billio & Giacomelli, 2022; Devalle et al., 2017). These results underscore the importance of considering temporal and strategic dimensions when evaluating the interplay between sustainability and financial performance in credit risk models.

5. Conclusion

Global banks are increasingly recognizing that strong ESG performance is not merely a reputational asset but also a financial asset. This study shows that banks with higher ESG scores tend to secure better credit ratings, reflecting greater trust from rating agencies and investors. However, the findings also reveal a trade-off: while ESG initiatives enhance long-term credibility, they may temporarily reduce profitability, as evidenced by lower EBIT. Moreover, the relationship between operational efficiency and credit ratings becomes more complex when ESG is considered, suggesting that high ESG performance can alter how efficiency is interpreted in risk assessments. For global banks, this means ESG is no longer a peripheral concern but a strategic lever that must be carefully aligned with financial and operational goals.

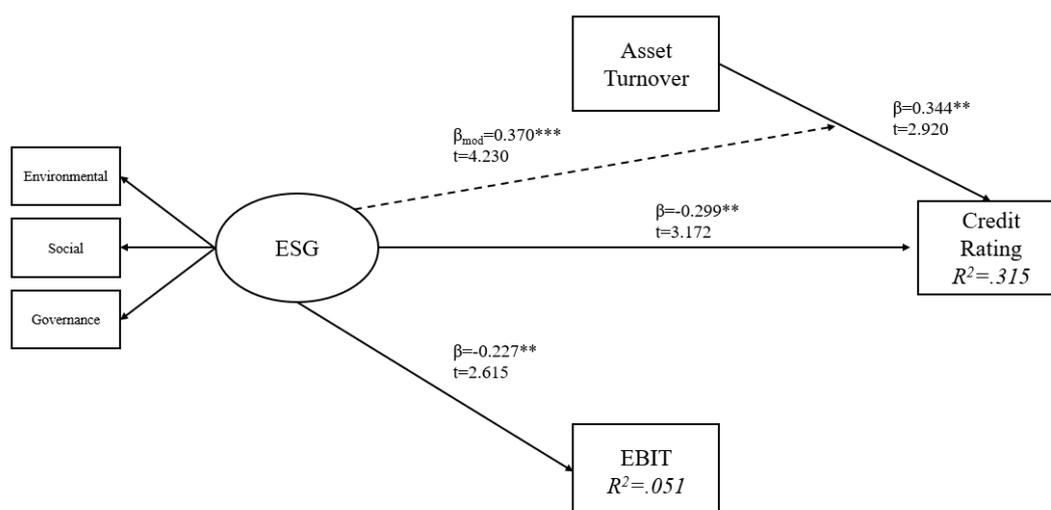


Figure 3. Final Model: Sustainability-Integrated Credit Rating Model for Global Banks. $^{**}p < .01$, $^{***}p < .001$. Source: Author

Figure 3 presents the final empirically tested model, Sustainability-Integrated Credit Rating Model for Global Banks, which encapsulates the direct and moderating effects of ESG performance, asset turnover, and EBIT on credit ratings. Although the R^2 value for EBIT is only 0.051, its inclusion in the final model is theoretically justified, as profitability is inherently influenced by a wide range of factors beyond ESG – such as market conditions, regulatory environments, and firm-specific strategies – making a low explanatory power from ESG alone both expected and consistent with prior research (Henkel et al., 2024; Kim & Li, 2021).

ESG as a Direct Predictor of Credit Ratings. For global banks operating in an increasingly transparent and risk-sensitive financial environment, ESG performance has become a core driver of creditworthiness. Rating agencies no longer evaluate institutions solely on traditional financial metrics; they increasingly incorporate ESG factors into their assessments. Banks with firm ESG profiles are viewed as more resilient, better governed, and less exposed to reputational, regulatory, and environmental risks. This translates into higher credit ratings, which, in turn, lowers the cost of capital and improves access to funding.

The direct link between ESG scores and credit ratings reflects a shift in how risk is perceived. A bank that demonstrates robust environmental policies, sound governance structures, and strong social responsibility is seen as better positioned to navigate long-term challenges – from climate-related disruptions to stakeholder scrutiny. These institutions signal stability and forward-thinking leadership, qualities that rating agencies increasingly reward.

ESG's Influence on Financial Indicators. While ESG performance is increasingly recognized as a driver of institutional credibility, its impact on core financial indicators such as profitability and operational efficiency presents a more complex picture for global banks. On one hand, ESG investments – such as climate risk mitigation, governance reforms, and social responsibility programs – can enhance long-term resilience and stakeholder trust. However, these initiatives often require substantial upfront costs, which may temporarily strain profitability metrics such as EBIT. For banks, this means that ESG-driven strategies may not immediately translate into higher earnings, but they contribute to a more stable and risk-aware operating environment.

Operational efficiency, measured through asset turnover, also interacts with ESG in nuanced ways. Banks that excel in ESG may already be perceived as low-risk institutions, thereby reducing the marginal impact of efficiency gains on credit ratings. In other words, once a bank demonstrates strong ESG credentials, additional improvements in asset utilization may not significantly shift how rating agencies assess its creditworthiness. This suggests that ESG performance can reshape the financial narrative – where sustainability signals strength, and traditional metrics like EBIT and asset turnover must be interpreted in light of broader strategic priorities.

Financial Indicators and Credit Ratings. In the credit evaluation of global banks, financial indicators such as asset turnover and EBIT continue to play a central role. However, their influence is evolving in light of broader strategic priorities. Asset turnover, which reflects how efficiently a bank uses its assets to generate revenue, is traditionally regarded as an indicator of operational strength. However, in today's risk-sensitive environment, high asset turnover may also signal aggressive growth strategies or lean asset structures, raising concerns about long-term stability. Credit rating agencies are increasingly looking beyond raw efficiency and asking whether such performance is sustainable and aligned with prudent risk management.

Similarly, EBIT – an indicator of core profitability – remains a key measure of a bank's ability to service debt and absorb shocks. However, as banks invest more heavily in ESG initiatives, short-term EBIT figures may not fully capture the strategic value of those investments. For example, expenditures on climate risk mitigation, governance reforms, or social programs may reduce immediate earnings but strengthen the institution's long-term resilience and stakeholder trust. Rating agencies are beginning to recognize this shift, placing greater emphasis on the quality and sustainability of earnings rather than their magnitude alone.

Moderating Role of ESG. As ESG performance becomes a central pillar of institutional strategy, its influence extends beyond direct impact – it also reshapes how traditional financial indicators are interpreted in credit assessments. For global banks, this means that ESG does not merely add value; it also alters how rating agencies assess other aspects of financial performance.

Take operational efficiency, for example. A bank with high asset turnover is typically regarded as effectively managing its resources. However, when that same bank also has strong ESG credentials, the efficiency signal may be interpreted differently. Rating agencies might view the combination as a sign of aggressive growth or risk-taking, especially if ESG efforts already convey stability and resilience. In this context, ESG can dilute the value added by efficiency by signaling that the institution has already addressed key risk factors through sustainability practices.

Similarly, ESG can influence how profitability is weighed. While strong earnings are always important, rating agencies may place less emphasis on short-term profitability if a bank demonstrates long-term value creation through ESG investments. This shift reflects a broader trend: credit ratings are increasingly shaped by the extent to which financial performance aligns with responsible governance, environmental stewardship, and social impact.

This study provides robust empirical evidence that ESG performance plays a critical role in shaping the creditworthiness of the world's largest banks. By positioning ESG as the central construct and integrating it with traditional financial indicators such as asset turnover and EBIT, the research offers a multidimensional view of how sustainability and financial performance jointly influence credit ratings. The findings confirm that ESG has a significant direct effect on credit ratings and a moderating effect on the relationship between operational efficiency and creditworthiness. Although the influence of EBIT was less significant, the study underscores the growing importance of non-financial metrics in credit evaluation frameworks.

5.1 Managerial Implications

The findings of this study offer several practical insights for executives, sustainability officers, and credit risk managers:

1. **ESG as a Strategic Lever for Creditworthiness:** The significant direct effect of ESG performance on credit ratings underscores the importance of integrating ESG into core business strategy. Managers should not treat ESG as a compliance obligation or a reputational tool alone, but as a strategic asset that can enhance creditworthiness and reduce the cost of capital.
2. **A Complex Interaction of ESG and Operational Efficiency:** The significant moderating effect of ESG on the relationship between asset turnover and credit ratings suggests that high ESG performance may weaken the beneficial effect of asset turnover on credit ratings. This implies that when ESG scores are already substantial, additional gains in operational efficiency may not further improve credit ratings and could even be perceived as risk-enhancing if they signal aggressive asset utilization. Managers should therefore carefully align ESG initiatives with operational strategies, ensuring that efficiency improvements are not pursued at the expense of perceived stability or sustainability. Rather than assuming a purely additive effect, executives should recognize that the value of operational efficiency may be context-dependent, particularly in institutions that already demonstrate strong ESG credentials.
3. **ESG Investment Requires Long-Term Perspective:** The findings imply that ESG investments may not yield immediate financial returns but can enhance long-term resilience and stakeholder trust. Executives should communicate this long-term value proposition to shareholders and boards to justify sustained ESG spending.

5.2 Theoretical Implications

In addition to the empirical validation, the study contributes to theoretical advancement by integrating seven foundational frameworks – Triple Bottom Line, Stakeholder Theory, Legitimacy Theory, Resource-Based View, Sustainable Performance Accounting, Signaling Theory, and ESG – into a unified conceptual model. This integration not only enhances the research's explanatory power but also bridges the gap between sustainability and financial risk assessment.

This study makes a moderate to substantial contribution to the body of knowledge on ESG-finance integration by empirically validating ESG performance as a key determinant of credit ratings in the global banking sector. Through a well-structured operational and final model, the research demonstrates that ESG not only directly influences creditworthiness but also significantly moderates the relationship between operational efficiency and credit ratings. Although the effects of profitability (EBIT) were less pronounced, the findings reinforce the financial materiality of ESG, particularly with respect to operational performance.

5.3 Recommendations

Future research should extend the analysis across multiple fiscal years to capture the evolving impact of ESG strategies on financial performance and credit ratings. A longitudinal approach would help assess how sustained ESG investments affect profitability, efficiency, and risk perception, particularly as regulatory standards and investor expectations continue to evolve. Additionally, expanding the sample to include mid-sized and regional banks could reveal sector-specific dynamics and provide a more inclusive view of ESG integration across the banking industry.

It would also be valuable to broaden the range of financial variables beyond EBIT and asset turnover. Including metrics such as return on equity (ROE), cost-to-income ratio, liquidity ratios, and leverage could offer deeper insights into how ESG interacts with different dimensions of financial health. Moreover, disaggregating ESG into its individual pillars – environmental, social, and governance – may uncover which components are most influential in shaping credit ratings. This expanded scope would support more targeted strategies for banks aiming to align sustainability with financial performance and risk management.

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Article

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Abstract: This article addresses the problem of improving the convergence order and stability of iterative methods for solving nonlinear equations. The main objective is to design a new multipoint iterative family with sixth-order convergence and to analyze both its convergence behavior and complex dynamics. The methodology combines the theoretical analysis of the convergence order, the derivation of the associated rational operator, and the use of complex dynamics tools such as stability surfaces, parameter planes, and dynamical planes. Numerical experiments conducted on nonlinear test equations confirm the results obtained from the convergence and stability analysis. The proposed method achieves high accuracy in few iterations, maintaining the Approximate Computational Order of Convergence (ACOC) around six and exhibiting competitive efficiency compared to classical methods such as Newton, Ostrowski, Jarratt, and CMT. The conclusions highlight the robustness of the family with respect to initial conditions. The findings have theoretical implications for the design of high-order iterative methods and practical implications for solving scientific and engineering problems more efficiently.

Keywords: complex dynamic, multi-step iterative methods, nonlinear equations, stability.

1. Introduction

To solve problems in science and engineering, it is common to formulate a nonlinear equation or a system of nonlinear equations, depending on the number of variables or the specific problem conditions. This type of equation arises in chemical processes, astronomical applications, polynomial interpolation, and the discretization of one-dimensional boundary value problems, among others. However, due to their nonlinear nature, obtaining exact solutions through traditional algebraic techniques is often highly complex or even unfeasible. In such cases, it becomes necessary to resort to iterative methods, which allow the solution to be approximated from an initial estimate and generate a sequence of values that, under certain conditions, may converge to the exact solution.

The resolution of nonlinear equations and systems by iterative methods has been, and continues to be, a recurring topic in numerical analysis, as evidenced by numerous publications (Artidiello, 2014; Moscoso-Martínez et al., 2023; Ortega & Rheinboldt, 1970; Traub, 1964), among others. One of the most well-known iterative methods for solving a nonlinear equation $f(x) = 0$ is Newton's method, which is given by the following expression:

$$x_{k+1} = x_k - \frac{f(x_k)}{f'(x_k)}, \quad k = 0, 1, 2, \dots$$

Nevertheless, this method exhibits limitations that motivate the search for new schemes with improved convergence properties.

The present research proposes a multipoint iterative family of order six for solving nonlinear equations. Because the proposed family depends on a parameter, the method's behavior may vary significantly with its value. For this reason, a convergence analysis is carried out to determine the method's order as a function of this parameter. Furthermore, a dynamical analysis is incorporated to identify the most stable and efficient elements of the family, thereby facilitating its application in numerical tests with nonlinear functions of greater complexity.

2. Literature Review

The resolution of nonlinear and linear systems of equations is a central problem in numerical analysis, with applications in physics and chemistry, boundary value problems, and polynomial interpolation. Since obtaining exact solutions is often intractable, numerous iterative methods have been developed with different structures and convergence orders.

In recent literature, several multipoint schemes of varying order have been introduced. Singh (2018) designed a Steffensen-type method of order five for nonlinear systems, while Chicharro et al. (2019) proposed a biparametric family of order six, combining Newton's and Traub's methods. More recently, Cordero et al. (2024) introduced an innovative technique that increases the order of convergence by three without relying on Jacobian matrices, demonstrating strong efficiency in biological models.

The pursuit of higher orders has motivated the development of more advanced schemes. Shams et al. (2022) constructed a three-step family with order eight, and Wang (2021) also proposed a multipoint method for nonlinear systems, achieving order eight. On the other hand, Tao & Madhu (2019) designed a scheme with order sixteen, although at a high computational cost. It is worth noting, however, that not all these studies include complex dynamics or stability analysis. For instance, Wang (2021), despite achieving order eight, did not address stability, thereby limiting understanding of the scheme's global behavior.

In recent years, parametrized iterative families have been developed that integrate tools from fundamental and complex dynamics to characterize the stability of fixed points and the structure of basins of attraction (Khirallah & Alkhomsan, 2022). This work highlights that dynamic analysis is an essential complement to classical convergence studies, as it provides insights into stability regions and chaotic behaviors.

From this overview, it is evident that most existing methods exhibit convergence orders between three and six. Moreover, complete dynamical studies are not always included. Consequently, there is a clear research gap for designing schemes that combine high convergence order with a comprehensive stability analysis. The iterative family proposed in this work addresses this gap by introducing a sixth-order multipoint scheme supported by theoretical convergence analysis and complex dynamical study.

3. Material and Methods

The research methodology adopted in this work is both theoretical and applied. A new step within an iterative family is proposed to increase the order of convergence without significantly raising the computational cost. In the theoretical phase, concepts and theorems from numerical analysis will be employed to rigorously establish the order of convergence of the new scheme. Likewise, specific conditions on the parameter under consideration will be analyzed to simplify the method's general expression.

The theoretical order of convergence will be contrasted with the approximate computational order of convergence (ACOC), following the proposal of Cordero and Torregrosa (2007). To analyze the method's dynamic behavior, a wide range of initial conditions will be considered. The corresponding orbits will be constructed from these, and their final states will be identified. This analysis will allow the generation of basins of attraction, which illustrate the regions of the plane where the method exhibits greater stability. A predefined error tolerance and a maximum number of iterations will define the visualization criterion. In addition, the effects of the parameter on the method's stability and rate of convergence, as well as its interactions with the different fixed points, will be examined.

The applied research will corroborate theoretical results. For this purpose, the scheme will be applied to low-order nonlinear systems and to systems with exponential, logarithmic, and trigonometric equations. MATLAB will be used for computational calculations to verify the theoretical results obtained. Both MATLAB and Mathematica will be employed to generate graphs.

4. Results

4.1 Development of the New Iterative Family

The starting point is the fourth-order iterative method proposed by Artidiello (2014), whose expression is

$$\begin{cases} y_k = x_k - \frac{f(x_k)}{f'(x_k)}, & k = 0, 1, 2, \dots, \\ x_{k+1} = y_k - \left(1 + 2 \frac{f(y_k)}{f(x_k)}\right) \frac{f(y_k)}{f'(x_k)}. \end{cases}$$

It is intended to improve this method; for this purpose, a third step is proposed in Moscoso-Martínez et al. (2023). By incorporating this third step into the method, a new triparametric iterative scheme is obtained.

$$\begin{cases} y_k = x_k - \frac{f(x_k)}{f'(x_k)}, & k = 0, 1, 2, \dots, \\ z_k = y_k - (1 + 2s_k) \frac{f(y_k)}{f'(x_k)}, \\ x_{k+1} = z_k - (\alpha + \beta s_k + \gamma t_k) \frac{f(z_k)}{f'(x_k)}, \end{cases}$$

where $s_k = \frac{f(y_k)}{f(x_k)}$ and $t_k = \frac{f'(x_k)}{f[x_k, y_k]}$, where $f[x_k, y_k]$ is the divided difference operator defined in , with α , β and γ being arbitrary parameters.

4.2 Convergence Analysis of the New Family

This section presents the convergence analysis of the new triparametric iterative family. Furthermore, a strategy is proposed to reduce the triparametric scheme to a uniparametric one to accelerate convergence.

Theorem 1. Let $f: C \subseteq \mathbb{R} \rightarrow \mathbb{R}$ be a sufficiently differentiable function on an open and connected set C , and let $\xi \in C$ be a root of $f(x)$ such that f' is continuous at ξ and $f'(\xi) \neq 0$. Then, if x_0 is an initial guess sufficiently close to ξ the members of the family converge to ξ with order of convergence four for the error equation being

$$e_{k+1} = -(c_2(5c_2^2 - c_3)(\alpha + \gamma - 1))e_k^4 + \mathcal{O}(e_k^5),$$

where $e_k = x_k - \xi$ and $c_j = \frac{1}{j!} \frac{f^{(j)}(\xi)}{f'(\xi)}$, for $j = 2, 3, \dots$

Proof. Expanding $f(x_k)$ and $f'(x_k)$ around ξ , we obtain

$$\begin{aligned} f(x_k) &= f(\xi) + f'(\xi)e_k + \frac{1}{2!}f''(\xi)e_k^2 + \dots + \frac{1}{6!}f^{(vi)}(\xi)e_k^6 + \mathcal{O}(e_k^7) \\ &= f'(\xi) \left(e_k + \frac{1}{2!} \frac{f''(\xi)}{f'(\xi)} e_k^2 + \dots + \frac{1}{6!} \frac{f^{(vi)}(\xi)}{f'(\xi)} e_k^6 + \mathcal{O}(e_k^7) \right) \\ &= f'(\xi) (e_k + c_2 e_k^2 + c_3 e_k^3 + c_4 e_k^4 + c_5 e_k^5 + c_6 e_k^6 + \mathcal{O}(e_k^7)). \end{aligned}$$

$$\begin{aligned} f'(x_k) &= f'(\xi) + f''(\xi)e_k + \frac{1}{2!}f'''(\xi)e_k^2 + \dots + \frac{1}{6!}f^{(v)}(\xi)e_k^5 + \mathcal{O}(e_k^6) \\ &= f'(\xi) \left(1 + \frac{f''(\xi)}{f'(\xi)} e_k + \frac{1}{2!} \frac{f'''(\xi)}{f'(\xi)} e_k^2 + \dots + \frac{1}{6!} \frac{f^{(v)}(\xi)}{f'(\xi)} e_k^5 + \mathcal{O}(e_k^6) \right) \\ &= f'(\xi) (1 + 2c_2 e_k + 3c_3 e_k^2 + 4c_4 e_k^3 + 5c_5 e_k^4 + 6c_6 e_k^5 + \mathcal{O}(e_k^6)), \end{aligned}$$

where $c_j = \frac{1}{j!} \frac{f^{(j)}(\xi)}{f'(\xi)}$, $j = 2, 3, \dots$

Therefore, using $f(x_k)$ and $f'(x_k)$, the first step of the family is:

$$y_k - \xi = c_2 e_k^2 + (-2c_2^2 + 2c_3) e_k^3 + (4c_2^3 - 7c_2 c_3 + 3c_4) e_k^4 + (-8c_2^4 + 20c_2^2 c_3 - 6c_3^2 - 10c_2 c_4 + 4c_5) e_k^5 + (16c_2^5 - 52c_2^3 c_3 + 28c_2^2 c_4 - 17c_3 c_4 + c_2(33c_3^2 - 13c_5) + 5c_6) e_k^6 + \mathcal{O}(e_k^7).$$

Using the expression of y_k the expansion corresponding to $f(y_k)$ is:

$$f(y_k) = f'(\xi)(c_2 e_k^2 + 2(-c_2^2 + c_3) e_k^3 + (5c_2^3 - 7c_2 c_3 + 3c_4) e_k^4 - 2(6c_2^4 - 12c_2^2 c_3 + 3c_3^2 + 5c_2 c_4 - 2c_5) e_k^5 + (28c_2^5 - 73c_2^3 c_3 + 34c_2^2 c_4 - 17c_3 c_4 + c_2(37c_3^2 - 13c_5) + 5c_6) e_k^6 + \mathcal{O}(e_k^7)).$$

This implies that, with $f(x_k)$, $f'(x_k)$, and $f(y_k)$, the second step of the family is given by

$$z_k - \xi = (5c_2^3 - c_2 c_3) e_k^4 - 2(18c_2^4 - 16c_3 c_2^2 + c_4 c_2 + c_3^2) e_k^5 + (170c_2^5 - 262c_3 c_2^3 + 48c_4 c_2^2 + (66c_3^2 - 3c_5) c_2 - 7c_3 c_4) e_k^6 + \mathcal{O}(e_k^7).$$

The expansion of $f(z_k)$ is

$$f(z_k) = f'(\xi) \left((5c_2^3 - c_2 c_3) e_k^4 - 2(18c_2^4 - 16c_3 c_2^2 + c_4 c_2 + c_3^2) e_k^5 + (170c_2^5 - 262c_3 c_2^3 + 48c_4 c_2^2 + (66c_3^2 - 3c_5) c_2 - 7c_3 c_4) e_k^6 + \mathcal{O}(e_k^7) \right).$$

The error equation obtained by using $f(x_k)$, $f'(x_k)$, $f(y_k)$, and $f(z_k)$ is

$$e_{k+1} = -(c_2(5c_2^2 - c_3)(\alpha + \gamma - 1)) e_k^4 + (c_2^4(46\alpha - 5\beta + 41\gamma - 36) + c_3 c_2^2(-34\alpha + \beta - 33\gamma + 32) + 2c_3^2(\alpha + \gamma - 1) + 2c_2 c_4(\alpha + \gamma - 1)) e_k^5 + (c_2^5(-262\alpha + 61\beta - 206\gamma + 170) + c_3 c_2^3(345\alpha - 47\beta + 299\gamma - 262) + 2c_4 c_2^2(-26\alpha + \beta - 25\gamma + 24) + 7c_3 c_4(\alpha + \gamma - 1) + c_2(c_3^2(-73\alpha + 4\beta - 69\gamma + 66) + 3c_5(\alpha + \gamma - 1))) e_k^6 + \mathcal{O}(e_k^7).$$

Which completes the proof.

Theorem 2. Let $f: C \subseteq \mathbb{R} \rightarrow \mathbb{R}$ be a sufficiently differentiable function on an open and connected set C , and let $\xi \in C$ be a root of $f(x)$ such that f' is continuous at ξ and $f'(\xi) \neq 0$. Then, if x_0 is an initial guess sufficiently close to ξ the members of the family converge to ξ with an order of convergence of six whenever $\beta = 1 + \alpha$ and $\gamma = 1 - \alpha$ with the error equation being

$$e_{k+1} = c_2(5c_2^2 - c_3)((5 + \alpha)c_2^2 - c_3) e_k^6 + \mathcal{O}(e_k^7).$$

Proof. It is possible to increase the order of convergence of the scheme; to do so, the terms e_k^4 and e_k^5 in the error expression, the expression must be canceled. Therefore, the parameters must satisfy the following system of equations.

$$\begin{cases} \alpha + \gamma = 1, \\ 46\alpha - 5\beta + 41\gamma = 36, \\ -34\alpha + \beta - 33\gamma = -32. \end{cases}$$

By manipulating the equations, the following expressions are obtained:

$$\beta = 1 + \alpha \text{ and } \gamma = 1 - \alpha,$$

and substituting the parameters, the new error equation is obtained

$$e_{k+1} = c_2(5c_2^2 - c_3)((5 + \alpha)c_2^2 - c_3)e_k^6 + \mathcal{O}(e_k^7).$$

Which proves the statement. \square

From Theorem 2, it follows that if only the parameter α is kept, the new three-parameter iterative family reduces to a one-parameter family with order of convergence six, for any real or complex values of the parameters, provided that the condition is satisfied. The previous analysis has been developed assuming that ξ is a simple root. However, the family can be extended to the case of multiple roots by relying on the modified Newton's method for roots with multiplicity m , whose expression is given by

$$x_{k+1} = x_k - m \frac{f(x_k)}{f'(x_k)},$$

so that the order of convergence can be preserved without requiring significant modifications to the expression of the proposed family.

4.3 Stability analysis

This section focuses on the study of the dynamic properties of the rational operator determined by the iterative family. The dynamic analysis provides important information on the stability of each family member, depending on the initial approximations used. A rational operator will be obtained to conduct the analysis, thereby enabling the construction of parameter spaces and dynamical planes. These representations in the complex plane allow us to observe the behavior of the method as a function of the parameter α and to study the basins of attraction, fixed points, and attractors. The rational operator of the family can be constructed for any nonlinear function $f(x)$. In this case, it will be built from a quadratic polynomial, and the results obtained will then be extrapolated to functions of greater complexity.

Theorem 3. Let $p(x) = (x - a)(x - b)$ be a generic polynomial with roots $a, b \in \mathbb{R}$. Then, the rational operator $O_\alpha(z)$ associated with the family and applied to $p(x)$ is

$$O_\alpha(z) = \frac{z^6(z^2 + 4z + 5)M(z)}{(5z^2 + 4z + 1)N(z)}$$

where $\alpha \in \mathbb{C}$ is an arbitrary parameter, and moreover $M(z)$ and $N(z)$ are polynomials depending on the parameter $\alpha \in \mathbb{C}$.

Proof. We consider the generic polynomial, $p(x) = (x - a)(x - b)$, where $a, b \in \mathbb{R}$ are its roots. By applying $p(x)$ to the family, we obtain a rational operator $R_p(x, \alpha, a, b)$ which depends on the roots of the polynomial $p(x)$. To eliminate the dependence on the roots, we consider the Möbius transformation defined as

$$H(z) = \frac{z - a}{z - b},$$

which satisfies $H(\infty) = 1$, $H(a) = 0$ and $H(b) = \infty$. Therefore, we obtain

$$O_\alpha(z) = (H \circ R \circ H^{-1})(z) = \frac{z^6(z^2 + 4z + 5)M(z)}{(5z^2 + 4z + 1)N(z)},$$

where the polynomials have been defined as

$$\begin{aligned} M_\alpha(z) &= \alpha + 5 + (34 + 4\alpha)z + (98 + 5\alpha)z^2 + 153z^3 + 149z^4 \\ &\quad + 92z^5 + 37z^6 + 9z^7 + z^8, \\ N_\alpha(z) &= 1 + 9z + 37z^2 + 92z^3 + 149z^4 + 153z^5 + (98 + 5\alpha)z^6 \\ &\quad + (34 + 4\alpha)z^7 + (5 + \alpha)z^8. \end{aligned}$$

Since the factor z^6 is involved in the operator $O_\alpha(z)$, it is confirmed that the iterative family has an order of at least six in the case of quadratic equations.

Once the rational operator $O_\alpha(z)$ has been obtained, it is possible to determine its fixed points and to classify them by stability.

Proposition 1. *Considering the equation $O_\alpha(z) = z$ the results obtained are:*

- $x = 0$ and $x = \infty$ are fixed points of $O_\alpha(x)$ for any $\alpha \in \mathbb{C}$.
- $x = 1$ is a strange, fixed point.
- The roots of the polynomial

$$k_\alpha(t) = 1 + 14t + 92t^2 + 377t^3 + 1079t^4 + (2263 - 5\alpha)t^5 + (3528 - 24\alpha)t^6 + (4088 - 42\alpha)t^7 + (3528 - 24\alpha)t^8 + (2263 - 5\alpha)t^9 + 1079t^{10} + 377t^{11} + 92t^{12} + 14t^{13} + t^{14}$$

denoted by $ex_i(\alpha)$ with $i = 1, 2, \dots, 14$, are strange, fixed points of the operator $O_\alpha(z)$.

To analyze the stability of the fixed points, one obtains

$$O'_\alpha(x) = \frac{-4x^6(1+x)^{10}(1+x^2)(1+x+x^2)Q(x)}{(-1-3x-4x^2-3x^3+(-1+2\alpha)x^4)^2(N(x))^2}$$

where has the polynom

$$Q(x) = -7(1+x)^4(1+x+x^2)^3(5+4x+5x^2) + 2\alpha(1+x)^2(1+x+x^2) + 2\alpha(1+x)^2(1+x+x^2)(35+46x+53x^2-22x^3-20x^4-22x^5 + 53x^6+46x^7+35x^8) + 2\alpha^2x(4+25x+72x^2+20x^3+2x^4-66x^5 + 2x^6+20x^7+72x^8+25x^9+4x^{10}).$$

Proposition 2. *The points $x = 0$ and $x = \infty$ are superattractors for all $\alpha \in \mathbb{C}$. The extraneous fixed point $x = 1$ satisfies the following:*

- If $|1445 + 25\alpha| > 6144$, then $x = 1$ is an attractor. Moreover, $x = 1$ cannot be a superattractor.
- If $|1445 + 25\alpha| < 6144$, then $x = 1$ is a repeller.
- If $|1445 + 25\alpha| = 6144$, then $x = 1$ is parabolic.

Let R_p be a rational operator determined by an iterative family, and let z_0 be a fixed point of R_p . Let $\alpha \in \mathbb{C}$ be a parameter of the iterative family. Then, the function $h: \mathbb{C} \rightarrow \mathbb{C}$ defined by $h(\alpha) = R'_p(z_0, \alpha)$ is called the stability function.

To numerically analyze the stability function, stability diagrams are used. These diagrams represent the surface generated in space by the function $\phi(\alpha) = |R'_p(z_0, \alpha)|$. On the Z-axis, the values of $|R'_p(z_0, \alpha)|$ are plotted, while on the XY-plane, the real and imaginary parts of $\alpha \in \mathbb{C}$ are represented. Through these visualizations, one can identify the regions where z_0 acts as a repulsive or attractive strange fixed point. The regions where the strange fixed point is repulsive are colored in gray, and those where it is attractive are shown in another color.

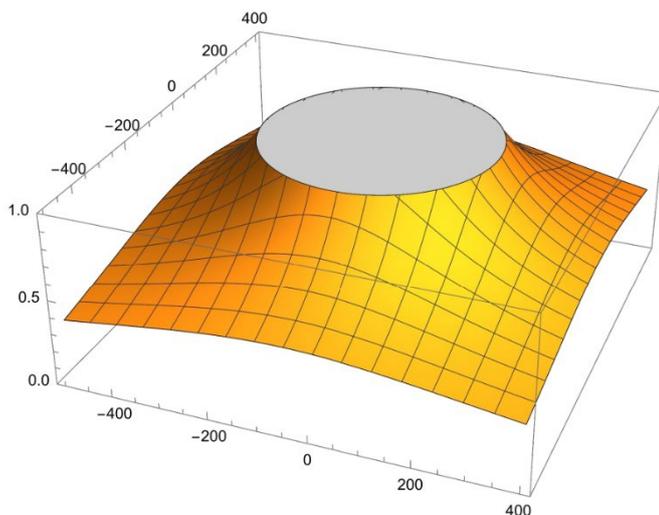


Figure 1. Stability surface for a strange, fixed point $x = 1$. Region of the complex plane: $[-450, 400] \times [-450, 400]$.

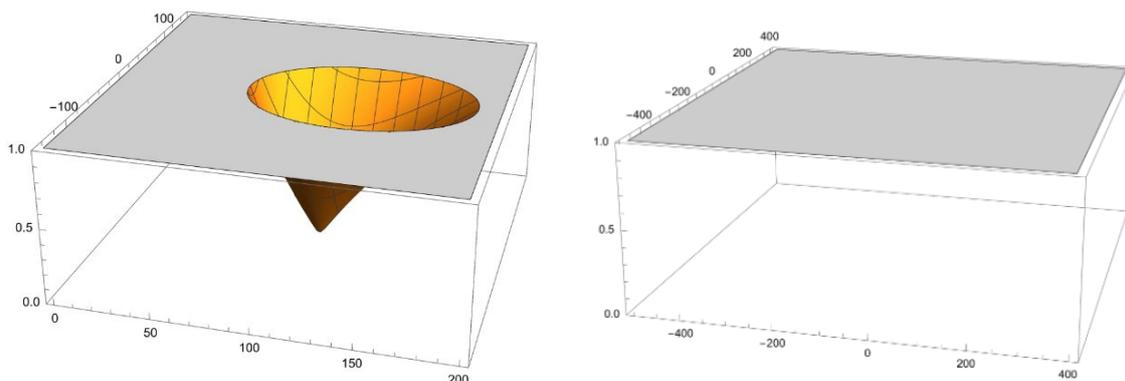


Figure 2. Stability surfaces for strange, fixed points $ex_i(\alpha)$ with $i = 1, 2, \dots, 14$. Región of the complex plane: $[0, 200] \times [-150, 150]$ and $[-450, 400] \times [-450, 400]$.

In the following result, an analysis of the critical points of the rational operator is carried out.

Proposition 3. *The critical points of the rational operator are $x = 0$ and $x = \infty$, while the free critical points are $x = -1$ and the roots of the polynomial*

$$h(t) = 150 + 30\alpha + (1155 + 133)t + (3908 + 192)t^2 + (7489 - 9\alpha)t^3 + (9276 - 92\alpha)t^4 + (7489 - 9\alpha)t^5 + (3908 + 192)t^6 + (1155 + 133)t^7 + (150 + 30\alpha)t^8,$$

and the roots of the polynomial, which are denoted by $cr_i(\alpha)$ for $i = 1, 2, \dots, 8$.

The parameter space is constructed by meshing the complex plane, where each point corresponds to a value of the parameter $\alpha \in \mathbb{C}$. For each value α , the free critical point $cr_i(\alpha)$ is taken as the initial guess. The mesh point is colored red if the method converges to a root; otherwise, it is colored black. To draw the parameter planes, a mesh of 1000×1000 points, a tolerance of 10^{-3} , and a maximum of 100 iterations have been considered. To construct the parameter planes, the code proposed by Chicharro et al. (2013) is used.

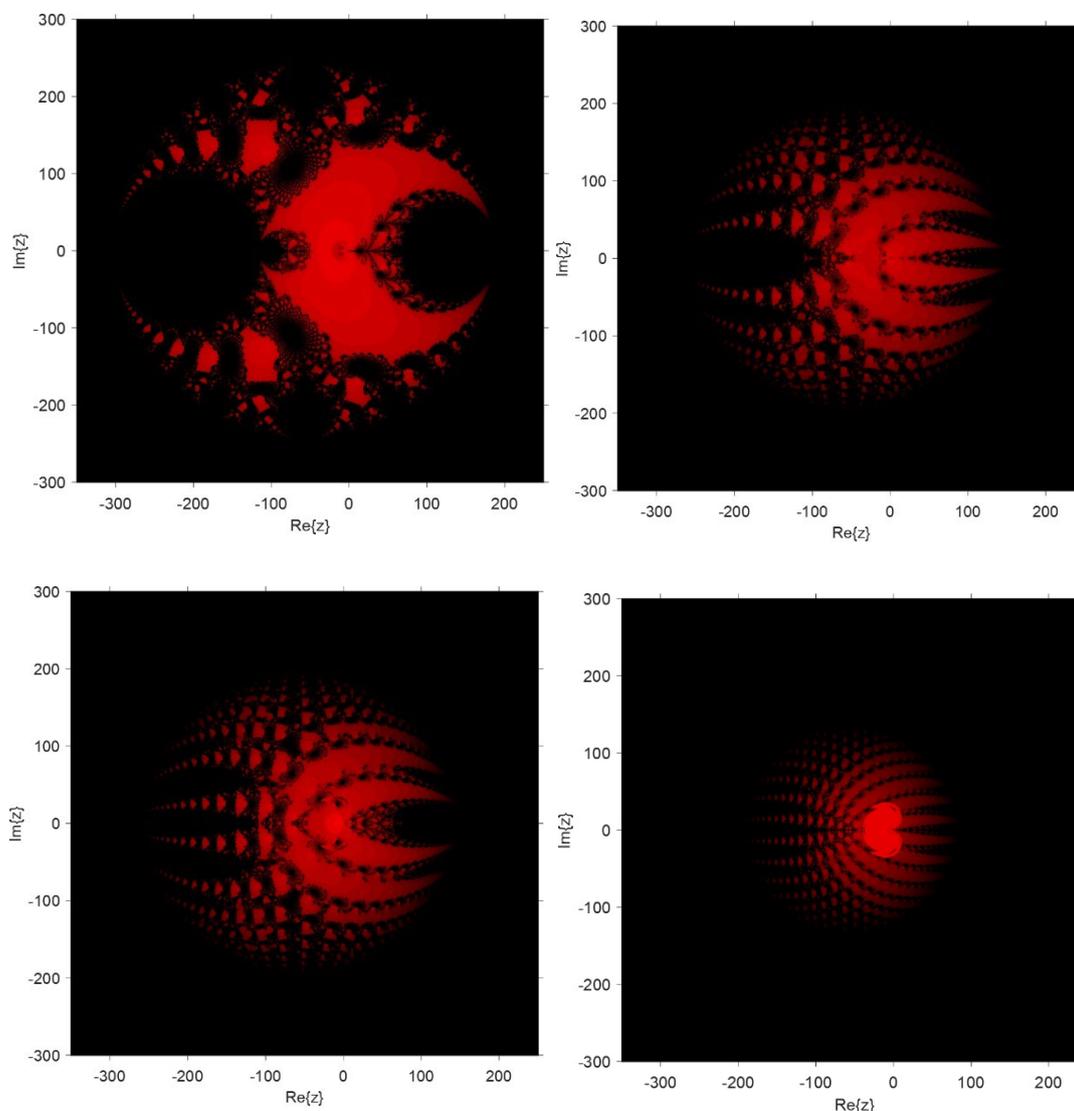


Figure 3. Parameter planes for the free critical points. Mesh size: 1000×1000 ; tolerance: 10^{-3} ; maximum iterations: 100; color map: red (convergent), black (non-convergent); region of the complex plane: $[-350, 250] \times [-300, 300]$.

The dynamical plane is a tool from complex dynamics that provides additional information beyond that obtained from stability surfaces and parameter planes. The dynamical plane is constructed similarly to the parameter plane: a grid of the complex plane is considered, and each point $x_0 \in \mathbb{C}$ represents an initial estimate for the iterative method. Depending on the convergence behavior, each point is represented by a specific color. For constructing the dynamical planes, the code proposed by Chicharro et al. (2013) is used. For the construction of the dynamical planes, values of the parameter α belonging to stable and unstable regions in the parameter planes are selected. A mesh of 1000×1000 points, a maximum of 100 iterations, and a tolerance of 10^{-3} are used.

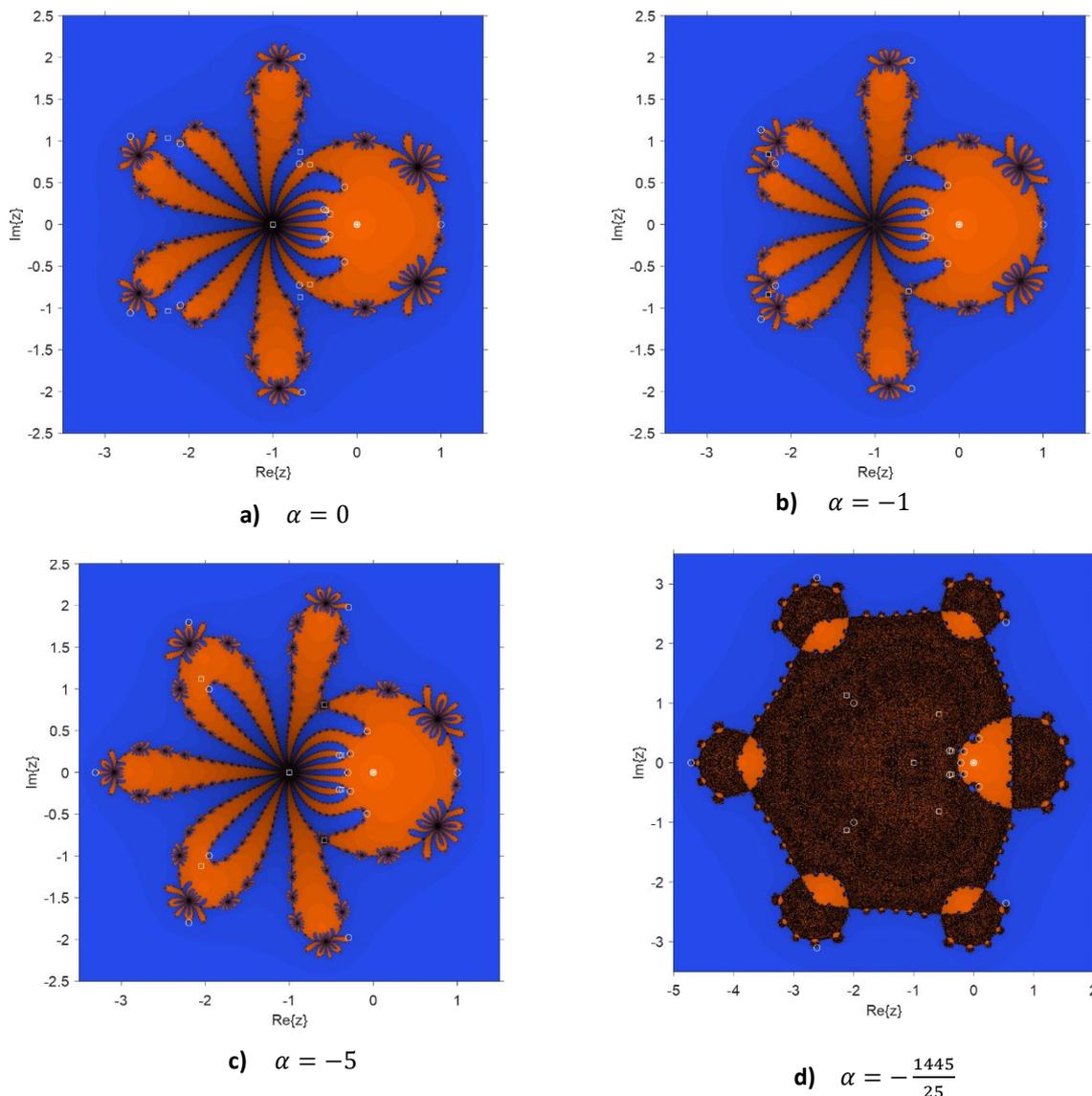
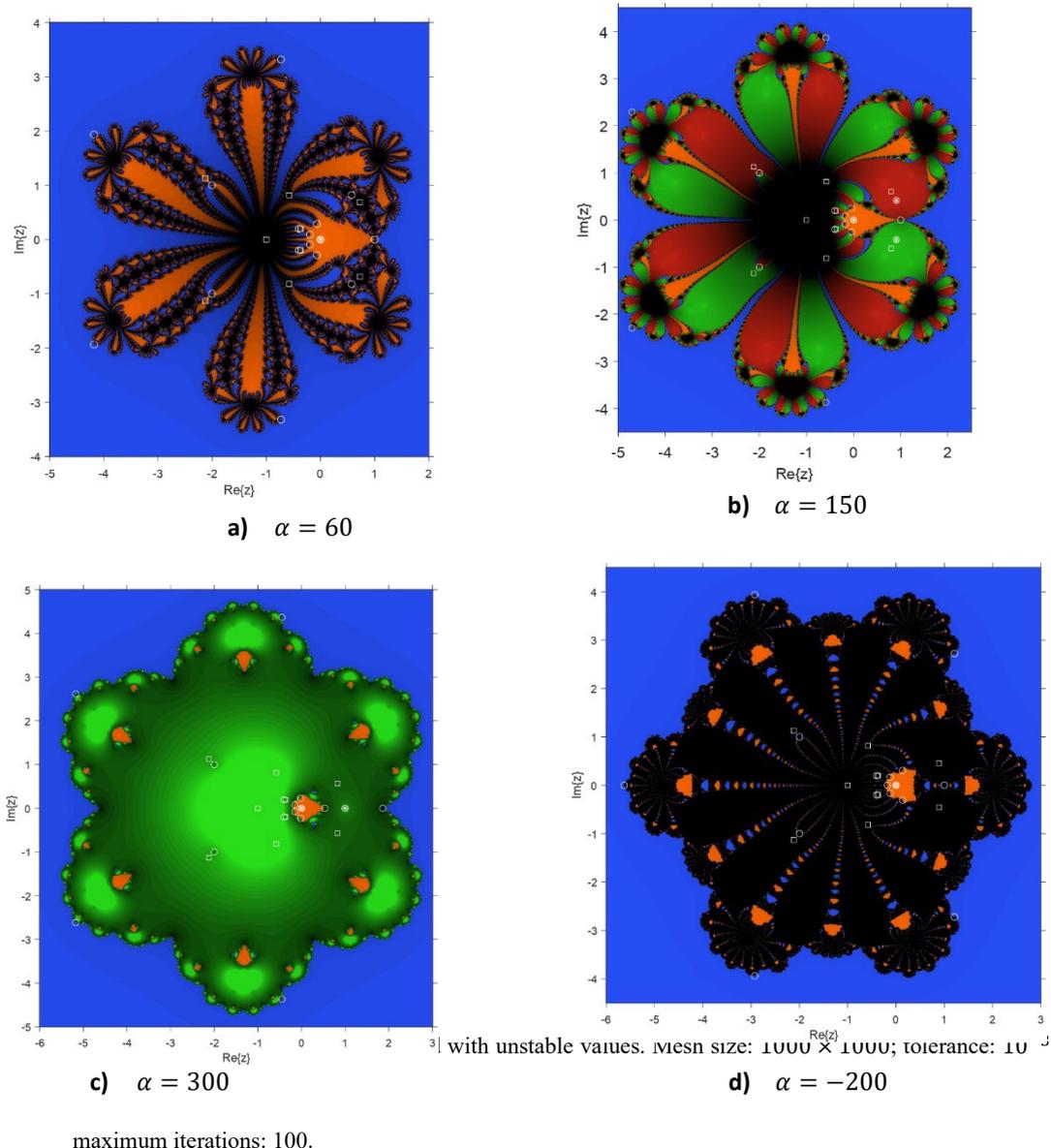


Figure 4. Dynamical planes associated with stable values. Mesh size: 1000×1000 ; tolerance: 10^{-3} ; maximum iterations: 100.

In Figure 4, the values $\alpha = 0, -1, -5$, and $-\frac{1445}{25}$ have been considered. It can be observed that for $\alpha = 0, -1$, and -5 , two basins of attraction appear: that of $x = 0$, represented in orange, and that of $x = \infty$ represented in blue, thus yielding a simple dynamic behavior for these parameters. However, when $\alpha = -\frac{1445}{25}$, black regions appear, which may indicate convergence issues of the method, even though α lies within a convergence region in the parameter planes.



In Figure 5, when taking $\alpha = 60$, three basins of attraction can be observed: that of $x = 0$, that of $x = \infty$ and a black region indicating non-convergent zones. For $\alpha = 150$, four basins of attraction appear: the green one, which is associated with the strange fixed point $x = 1$, and the black one, which indicates slow convergence. When $\alpha = 300$, the green region becomes considerably larger and is associated with the strange fixed point $x = 1$. For $\alpha = -200$, black regions are observed, indicating that the method is not stable for this parameter.

To quantify the regions observed in the dynamical planes, a color-based analysis was performed on the inner frame of each figure. The tones associated with convergence (blue and orange) were grouped together, while the remaining colors (including green, red, and black) were classified as non-convergent regions. This provides an approximate measure of the percentage of mesh points that converge to a root versus those that diverge or remain undefined.

Table 1. Percentage of mesh classified by convergence.

α	Convergence (%)	Non-convergence (%)
60	71.47	28.53
150	40.60	59.40
-200	36.98	63.02
300	27.76	72.24

When considering the value of $\alpha = 60$, it is observed that 71.47% of the grid points converge to the roots of the polynomial. However, when $\alpha = 150, -200, 300$, there is a higher percentage of initial grid points for which the method does not converge. This is due to the presence of other basins of attraction associated with the strange fixed points.

4. Discussion

In this section, several numerical tests will be carried out to confirm the validity of the results related to the convergence and stability of the family $M6(\alpha)$. To perform the numerical tests, one value of the parameter α that generates a stable method and another value of α that generates an unstable method will be considered, and each method will be applied to ten nonlinear equations. The expressions of these equations and their respective roots are shown in Table 2.

MATLAB 2022b is used for numerical tests, with variable-precision arithmetic with 500 mantissa digits. The stopping criterion is established as $|f(x_{k+1})| < 10^{-100}$ or $|x_{k+1} - x_k| < 10^{-100}$, with a maximum number of 30 iterations. The approximate computational order of convergence (ACOC) will be obtained to verify the theoretical order of convergence. If the method does not converge within 30 iterations, the ACOC is indicated as “nc”, and if the ACOC fails to stabilize, the symbol “-” is used.

Table 2. Nonlinear test equations.

Nonlinear equations	Roots
$f_1(x) = \cos(x) - 2x^2 + 1 = 0$	$\xi \approx 0.90036$
$f_2(x) = 2 + (x - 1)^3 + e^{x^2} = 0$	$\xi \approx -0.48322$
$f_3(x) = xe^x + \cos(x) - 3x^2 - 2 = 0$	$\xi \approx 1.95874$
$f_4(x) = \arctan(x^3) + \sqrt{x^2 + 2x} - 4 = 0$	$\xi \approx 1.78793$
$f_5(x) = \log(x^2 + 2) - x^3 + 1 = 0$	$\xi \approx 1.32435$

For the numerical experiments, the parameters $\alpha = 0$ and $\alpha = 300$ are chosen, where the former simplifies the rational operator and also provides a simple dynamical behavior, while the latter, according to Figure 5, exhibits an unstable behavior.

Table 3. Numerical results of $M6(0)$ on nonlinear equations (1/2).

Function	x_0	$ x_{k+1} - x_k $	$ f(x_{k+1}) $	Iterations	ACOC	Time
$x_0 \approx \xi$						
f_1	0.8	1.0243×10^{-34}	5.3686×10^{-204}	3	6.0634	0.06392
f_2	-0.5	8.5634×10^{-66}	1.5786×10^{-390}	3	5.9952	0.09636
f_3	1.9	2.1979×10^{-29}	8.9641×10^{-170}	3	6.0769	0.07919
f_4	1.7	2.6226×10^{-55}	1.1284×10^{-330}	3	6.0345	0.09936
f_5	1.3	4.5353×10^{-51}	4.2986×10^{-301}	3	6.0119	0.07426
$x_0 \approx 10\xi$						

Table 4. Numerical results of $M6(0)$ on nonlinear equations (2/2).

Function	x_0	$ x_{k+1} - x_k $	$ f(x_{k+1}) $	Iterations	ACOC	Time
f_1	8.0	1.6369×10^{-66}	8.9396×10^{-395}	5	5.9955	0.08241
f_2	-5.0	1.5400×10^{-34}	2.1337×10^{-198}	15	5.9537	0.31003
f_3	19.0	7.9402×10^{-93}	0	14	5.9996	0.25701
f_4	17.0	2.0179×10^{-73}	2.3415×10^{-439}	4	6.0089	0.11272
f_5	13.0	1.6049×10^{-28}	8.4429×10^{-166}	6	5.9010	0.11082

With $\alpha = 0$, the iterative family shows a highly stable and accurate performance, confirming an approximate convergence order of six in all analyzed cases. For initial conditions close to the root, the method converges in only three iterations, with minimal errors and residuals, demonstrating high numerical precision and low computational cost. Even when the initial point is farther from the root, the method preserves its stability and the same convergence order. However, it requires more iterations (4-15) and slightly longer execution times. Overall, the results confirm that the value $\alpha = 0$ provides an optimal performance within the family, combining efficiency, speed, and robustness with respect to variations in the initial condition.

Table 5. Numerical results of M6(300) on nonlinear equations.

Function	x_0	$ x_{k+1} - x_k $	$ f(x_{k+1}) $	Iterations	ACOC	Time
$x_0 \approx \xi$						
f_1	0.8	7.4561×10^{-22}	4.7700×10^{-125}	3	6.1290	0.06504
f_2	-0.5	1.4314×10^{-53}	1.9739×10^{-315}	3	5.9922	0.09011
f_3	1.9	2.5029×10^{-89}	0	4	5.9997	0.09704
f_4	1.7	7.3766×10^{-40}	9.9462×10^{-236}	3	6.0392	0.09768
f_5	1.3	3.0434×10^{-38}	2.5510×10^{-222}	3	6.0206	0.06722
$x_0 \approx 10\xi$						
f_1	8.0	nc	nc	nc	nc	nc
f_2	-5.0	nc	nc	nc	nc	nc
f_3	19.0	nc	nc	nc	nc	nc
f_4	17.0	7.6319×10^{-74}	1.2198×10^{-439}	4	5.9973	0.12416
f_5	13.0	nc	nc	nc	nc	nc

When comparing the results obtained for $\alpha = 300$ with those for $\alpha = 0$, it is observed that the iterative family M6(α) maintains an approximate convergence order of six and high numerical accuracy in both cases when the initial point is close to the root. For $\alpha = 300$, the method solves in three or four iterations, with errors and residuals on the order of $10^{-22} - 10^{-89}$ and $10^{-125} - 10^{-315}$, respectively, values comparable to those obtained with $\alpha = 0$. However, when analyzing more distant initial conditions, the behavior differs significantly: while for $\alpha = 0$ the method remains convergent in all cases, for $\alpha = 300$ the process diverges for most of the test functions, except for one case where it stabilizes and preserves the theoretical order. Consequently, although both parameter values yield efficient performance near the root, $\alpha = 0$ provides greater global stability, whereas $\alpha = 300$ exhibits a more restrictive and unstable dynamic when the initial condition varies.

Next, a comparative analysis will be carried out between a stable method of the family M6(α) and five iterative methods of different orders, to evaluate the numerical performance in solving nonlinear equations. The parameter $\alpha = -5$ is chosen, since a more simplified rational operator is obtained, which is

$$O_{-5}(z) = \frac{z^7(z^2 + 4z + 5)(z^7 + 9z^6 + 37z^5 + 92z^4 + 149z^3 + 153z^2 + 73z + 14)}{(5z^2 + 4z + 1)(1 + 9z + 37z^2 + 92z^3 + 149z^4 + 153z^5 + 73z^6 + 14z^7)}$$

Thus reducing the number of strange fixed points and free critical points. Moreover, $\alpha = -5$ belongs to the stable region in the parameter planes, and for $\alpha = -5$, according to Proposition 2, the strange fixed point $x = 1$ is repulsive.

The iterative methods considered in this study are the following:

- Newton’s method, denoted as NM, and its expression is

$$x_{k+1} = x_k - \frac{f(x_k)}{f'(x_k)}, \quad k = 0,1,2, \dots$$

- The method of Ostrowski (1960), denoted as MO and defined as

$$\begin{cases} y_k = x_k - \frac{f(x_k)}{f'(x_k)}, \\ x_{k+1} = y_k - \frac{f(x_k)}{f(x_k) - 2f(y_k)} \frac{f(y_k)}{f'(x_k)}, \end{cases} \quad k = 0,1,2, \dots$$

- The method of Jarratt (1969), denoted as MJ, and its expression is

$$\begin{cases} y_k = x_k - \frac{2f(x_k)}{3f'(x_k)}, \\ x_{k+1} = x_k - \frac{1f(x_k)}{2f'(x_k)} \left(\frac{3f'(y_k) + f'(x_k)}{3f'(y_k) - f'(x_k)} \right), \end{cases} \quad k = 0,1,2 \dots$$

- The sixth-order method proposed (Cordero et al., 2021), denoted as CMT, and its expression is

$$\begin{cases} y_k = x_k - \frac{f(x_k)}{f'(x_k)}, \\ z_k = y_k - \frac{f(y_k)}{2f[x_k, y_k] - f'(x_k)}, \\ x_{k+1} = z_k - (\beta + (1 + \beta)\mu_k + (1 - \beta)\nu_k) \frac{f(z_k)}{f'(x_k)}, \end{cases} \quad k = 0,1,2, \dots,$$

In Tables 6 and 7, an initial estimate close to the solution η will be taken to compare the results obtained.

Table 6. Numerical performance of iterative methods in nonlinear equations for $x_0 \approx \xi$ (1/2)

Function	Method	$ x_{k+1} - x_k $	$ f(x_{k+1}) $	Iterations	ACOC	Time
f_1 $x_0 = 0.8$	M6(-5)	3.2293×10^{-41}	1.10674×10^{-244}	3	6.2137	0.05451
	MN	1.7526×10^{-80}	7.0977×10^{-160}	7	2.0000	0.09936
	MO	1.3807×10^{-79}	2.5820×10^{-316}	4	4.0000	0.06377
	MJ	1.2735×10^{-79}	1.8607×10^{-316}	4	4.0000	0.12055
	CMT	7.1089×10^{-40}	1.3002×10^{-235}	3	6.0389	0.05087

Table 7. Numerical performance of iterative methods in nonlinear equations for $x_0 \approx \xi$. (2/2)

Function	Method	$ x_{k+1} - x_k $	$ f(x_{k+1}) $	Iterations	ACOC	Time
f_2 $x_0 = -0.5$	M6(-5)	3.1867×10^{-73}	2.5776×10^{-436}	3	6.067	0.08132
	MN	2.2370×10^{-88}	1.2994×10^{-175}	7	2.0000	0.07574
	MO	1.2311×10^{-86}	1.8457×10^{-344}	4	4.0000	0.05218
	MJ	3.2218×10^{-88}	7.1392×10^{-351}	4	4.0000	0.06462
	CMT	4.5277×10^{-44}	8.5943×10^{-261}	3	6.0180	0.06042
f_3 $x_0 = 1.9$	M6(-5)	2.3575×10^{-33}	1.17534×10^{-194}	3	6.2017	0.05984
	MN	6.5178×10^{-70}	4.7680×10^{-138}	7	2.0000	0.07021
	MO	1.2196×10^{-74}	2.7409×10^{-295}	4	4.0000	0.08726
	MJ	1.6662×10^{-74}	9.6986×10^{-295}	4	4.0000	0.06974

	CMT	3.1448×10^{-36}	1.0087×10^{-211}	3	6.0384	0.08516
f_4 $x_0 = 1.7$	M6(-5)	9.3647×10^{-54}	4.5613×10^{-321}	3	6.0247	0.08440
	MN	9.7673×10^{-53}	3.1751×10^{-105}	6	2.0000	0.13373
	MO	5.4549×10^{-98}	4.0911×10^{-391}	4	4.0000	0.07875
	MJ	7.8331×10^{-26}	9.6803×10^{-103}	3	4.0208	0.07885
	CMT	6.9953×10^{-55}	5.5267×10^{-328}	3	6.0235	0.08172
f_5 $x_0 = 1.3$	M6(-5)	1.1450×10^{-57}	7.4011×10^{-342}	3	6.0454	0.06332
	MN	4.6719×10^{-54}	8.6338×10^{-107}	6	2.0000	0.07306
	MO	3.4861×10^{-28}	3.0303×10^{-110}	3	4.0043	0.05021
	MJ	3.4529×10^{-28}	2.9109×10^{-110}	4	4.0043	0.06760
	CMT	4.4257×10^{-57}	5.4482×10^{-338}	3	6.0028	0.05720

In Tables 6 and 7, the initial approximation $x_0 \approx \eta$ has been considered. It is observed that Newton’s method requires the largest number of iterations for all equations, which was expected due to its quadratic order of convergence. Jarratt’s and Ostrowski’s methods exhibit similar behavior with respect to the number of iterations. The M6(-5) performs three iterations for all equations, as do the other seventh-order methods. Furthermore, the sixth-order methods, including M6(-5), yield similar results for the values of $|x_{k+1} - x_k|$ and $|f(x_{k+1})|$.

Table 8. Numerical performance of iterative methods in nonlinear equations for $x_0 \approx 10\xi$. (1/2)

Function	Method	$ x_{k+1} - x_k $	$ f(x_{k+1}) $	Iterations	ACOC	Time
f_1 $x_0 = 8.0$	M6(-5)	1.2871×10^{-95}	4.3603×10^{-508}	5	6.0085	0.08636
	MN	2.9167×10^{-59}	1.9657×10^{-117}	10	2.0000	0.10010
	MO	2.3390×10^{-29}	2.1262×10^{-115}	5	3.9947	0.07894
	MJ	1.6725×10^{-31}	5.5358×10^{-124}	5	3.9964	0.09117
	CMT	1.4919×10^{-17}	1.1107×10^{-101}	4	5.5594	0.06457
f_2 $x_0 = -5.0$	M6(-5)	3.4182×10^{-54}	3.0512×10^{-317}	14	5.9126	0.32615
	MN	2.8569×10^{-68}	8.9501×10^{-134}	22	2.0000	0.31122
	MO	4.4511×10^{-55}	1.7146×10^{-215}	10	4.0000	0.27329
	MJ	2.8811×10^{-46}	3.1665×10^{-180}	10	3.9998	0.24388
	CMT	1.6478×10^{-53}	3.3397×10^{-313}	9	5.9922	0.27125

Table 9. Numerical performance of iterative methods in nonlinear equations for $x_0 \approx 10\xi$. (2/2)

Function	Method	$ x_{k+1} - x_k $	$ f(x_{k+1}) $	Iterations	ACOC	Time
f_3 $x_0 = 19.0$	M6(-5)	2.5266×10^{-99}	0	13	5.9980	0.29081
	MN	4.2005×10^{-67}	1.9803×10^{-132}	28	2.0000	0.28778
	MO	5.3344×10^{-78}	1.0032×10^{-308}	13	4.0000	0.24844
	MJ	6.3608×10^{-65}	2.0597×10^{-256}	13	4.0000	0.26074
	CMT	4.3124×10^{-23}	6.7067×10^{-133}	11	5.8435	0.22709
f_4 $x_0 = 17.0$	M6(-5)	3.4438×10^{-71}	1.1281×10^{-425}	4	6.0066	0.12779
	MN	2.2233×10^{-67}	1.6452×10^{-134}	8	2.0000	0.13033
	MO	2.9920×10^{-91}	3.7029×10^{-364}	5	4.0000	0.12303
	MJ	5.0866×10^{-77}	1.7214×10^{-307}	5	4.0000	0.12738
	CMT	1.6918×10^{-72}	1.1057×10^{-433}	4	6.0061	0.12369
f_5 $x_0 = 13.0$	M6(-5)	2.3562×10^{-53}	5.6216×10^{-316}	6	5.9305	0.15132
	MN	6.9556×10^{-56}	1.9137×10^{-110}	13	2.0000	0.14343
	MO	7.7210×10^{-73}	7.2918×10^{-289}	7	4.0000	0.12614
	MJ	7.2577×10^{-73}	5.6821×10^{-289}	7	4.0000	0.16738
	CMT	2.4872×10^{-67}	1.7165×10^{-399}	6	5.9970	0.12466

The results show that the method M6(−5) stands out for achieving high levels of numerical accuracy in just a few iterations. In all cases, it attains residuals close to zero and extremely small differences between iterations (up to 10^{-99}), which indicates high stability and an excellent approximation to the root. Moreover, the obtained ACOC remains close to 6 in all experiments, thus confirming the theoretical order of convergence of the method.

In the previous tables, a comparison of the methods has been made in terms of ACOC, errors, and execution time. Now, the Ostrowski efficiency index (Ostrowski, 1960) will be used, which is defined as

$$EI = p^{1/d},$$

where p is the order of convergence of the method and d is the number of functional evaluations performed. The Ostrowski efficiency index is useful because it helps avoid artificial accelerations in iterative methods. It has been demonstrated that the family M6(α) has a convergence order of $p = 6$ and involves a total of four functional evaluations — three evaluations of the function f at the points x_k, y_k , and z_k , and one evaluation of its derivative f' at the point x_k . Therefore, based on the above information, the Ostrowski efficiency index is

$$EI = 6^{1/4} \approx 1.5650845801.$$

Table 10 presents a comparison of the Ostrowski efficiency index of the family M6(α) with the Newton, Ostrowski, Jarratt, and CMT methods.

Table 10. Comparison of the efficiency index.

Method	Functional evaluations (d)	Order (p)	EI
M6(α)	4 (3 f , 1 f')	6	$6^{1/4} \approx 1.5651$
MN	2 (1 f , 1 f')	2	$2^{1/2} \approx 1.4142$
MO	3 (2 f , 1 f')	4	$4^{1/3} \approx 1.5874$
MJ	3 (2 f , 1 f')	4	$4^{1/3} \approx 1.5874$
CMT	4 (3 f , 1 f')	6	$6^{1/4} \approx 1.5651$

The Kung–Traub conjecture (Kung & Traub, 1974) states that the convergence order of a memoryless iterative method with d functional evaluations per iteration is less than or equal to 2^{d-1} . When this bound is reached, the method is called optimal. Therefore, the theoretical efficiency frontier for the M6(α) family is $2^{4-1} = 8$; since this does not match the actual convergence order $p = 6$, the family is not optimal.

When compared with the previous methods, the M6(α) family proves to be more efficient than Newton's method and exhibits the same efficiency index (EI) as the CMT method. However, the Ostrowski and Jarratt methods have a slightly higher EI, which is to be expected since they are optimal methods. Although the proposed family is not optimal according to the Kung–Traub criterion, its convergence and stability properties make it a competitive option for high-precision computations.

5. Conclusions

In this work, a new iterative family has been developed to solve nonlinear equations. This family was constructed from the fourth-order uniparametric scheme proposed by Artidiello (2014), to which a third step based on the work of Moscoso-Martínez et al. (2023) was added. It was demonstrated that the new family for solving nonlinear equations has an order of convergence of 6; thus, the third step increases the convergence order by 2.

The research results inform the design of high-order iterative schemes, demonstrating that incorporating an adaptive third step can increase the order of convergence without significantly increasing computational cost. This reinforces the relevance of parameterized families for the construction and analysis of new rational operators, particularly through the combined use of tools from complex dynamics.

In the dynamic analysis of the family for solving the nonlinear equation, the rational operator was obtained using the polynomial $p(x) = (x - a)(x - b)$ and a Möbius transformation, which made it possible to determine its fixed and critical points. Through the parameter planes, the regions of the complex plane that define the values of the parameter α for which the methods of the family are stable have been identified. In the dynamical planes, the different basins of attraction are shown, with bold italic alpha values that generate both stable and unstable methods.

Numerical experiments confirm that, for specific parameter values, the proposed family outperforms classical methods such as Newton, Ostrowski, Jarratt, and CMT in both efficiency and accuracy, while maintaining a high order of convergence even under initial conditions far from the root. Overall, the results demonstrate the robustness, stability, and applicability of the new iterative family, thereby consolidating it as an effective tool for the numerical analysis of nonlinear equations. The proposed family achieves an appropriate balance between accuracy and efficiency, as indicated by the Ostrowski efficiency index ($EI \approx 1.565$) and the reduced number of functional evaluations per iteration. Moreover, the robustness analysis based on mesh-grid convergence percentages supports its practical adoption in scientific and engineering problems that require global stability and rapid convergence.

The iterative family was designed for solving nonlinear equations; however, it can be extended to the multidimensional case by adopting the corresponding notation. Therefore, one future research direction is to determine whether the order of convergence is preserved in the multidimensional setting. Additionally, a stability analysis could be performed using tools from fundamental dynamics, such as parameter lines and dynamical planes in the real plane.

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Theoretical Paper

Gobernanza pública y tecnologías emergentes en la Cuarta Revolución Industrial: tensiones, oportunidades y dilemas en América Latina

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Resumen: Este ensayo analiza críticamente la reconfiguración de la gestión pública en América Latina a partir de la Cuarta Revolución Industrial, con énfasis en tecnologías como la inteligencia artificial, el blockchain y el big data. El propósito es discutir, desde una perspectiva contextual, las oportunidades y los desafíos que enfrentan las administraciones públicas al incorporar estas herramientas, considerando explícitamente sus consecuencias éticas, legales y sociales. Se adopta un enfoque cualitativo basado en la revisión bibliográfica y en estudios de caso, a partir del cual se propone un marco conceptual organizado en cuatro dimensiones: (1) transformación tecnológico-digital, (2) participación y relación Estado-ciudadanía, (3) capacidades institucionales y regulación, y (4) estrategia pública latinoamericana. Los resultados sugieren que la adopción tecnológica puede fortalecer la eficiencia administrativa, mejorar la trazabilidad de los procesos, ampliar los mecanismos de transparencia y habilitar nuevas modalidades de interacción ciudadana. Sin embargo, también puede intensificar brechas preexistentes mediante la exclusión digital, los sesgos algorítmicos, la dependencia tecnológica y nuevas formas de vigilancia o control, con efectos diferenciados según las capacidades estatales y las desigualdades territoriales. Se argumenta que el Estado puede actuar como impulsor de la innovación pública cuando articula capacidades técnicas con legitimidad democrática, protección de derechos y gobernanza de datos. En conclusión, se sostiene que la modernización no deriva automáticamente de la digitalización: las tecnologías operan como dispositivos sociopolíticos que redistribuyen poder, riesgos y responsabilidades. En este marco, el desafío central consiste en avanzar hacia una gobernanza digital crítica e inclusiva que supere el enfoque tecnocrático y responda a las condiciones estructurales de la región.

Palabras clave: Brecha digital, Dispositivos de poder, Cuarta Revolución Industrial, Gestión pública digital, Inteligencia Artificial

1. Introducción

La Cuarta Revolución Industrial, definida por Schwab (2023) como una convergencia de tecnologías físicas, digitales y biológicas que transforman simultáneamente los sistemas sociales y económicos, ha provocado

profundos cambios en los procesos productivos, las dinámicas sociales y las estructuras económicas. En este escenario, las administraciones públicas tienen el reto de adaptarse a un entorno definido por tecnologías emergentes como la inteligencia artificial, el blockchain, el big data y la computación en el borde. Estas herramientas permiten transformar la gestión pública, promoviendo niveles más altos de eficiencia, transparencia y capacidad de respuesta a las necesidades de la ciudadanía. Sin embargo, esta transición enfrenta varios obstáculos, entre los que se destacan la desigualdad en el acceso a la tecnología, los riesgos éticos y legales y la resistencia al cambio en las burocracias tradicionales.

Se entiende la transformación de la gestión pública desde formas de gobernanza digital posweberianas; es decir, se toma distancia de los paradigmas tradicionales de la burocracia, así como de las perspectivas gerencialistas y de la Nueva Gestión Pública. Así, se articulan cuatro dimensiones clave que orientan nuestro marco conceptual. En primer lugar, una dimensión tecnológico-digital que promueve la reintegración institucional, la digitalización centrada en el ciudadano y la reorganización del aparato estatal mediante el uso intensivo de las tecnologías de la información (Dunleavy et al., 2006). En segundo lugar, una dimensión participativa y coproducida, en la que la ciudadanía no solo consume servicios públicos, sino que participa activamente en su diseño y provisión, generando valor público mediante relaciones sostenidas con las instituciones (Osborne & Stokosch, 2013). En tercer lugar, una dimensión institucional y situada, que resalta el papel del contexto político-administrativo en la forma en que las innovaciones son adoptadas, adaptadas o resistidas dentro de los marcos normativos y culturales existentes (Pollitt & Bouckaert, 2011). Finalmente, proponemos una dimensión estratégico-latinoamericana que concibe al Estado como actor político y agente innovador, capaz de liderar procesos de transformación institucional desde una visión contextualizada y con un enfoque de inclusión, lo cual resulta especialmente relevante en regiones marcadas por desigualdades estructurales (Ramírez-Alujas, 2012). Este marco nos permite posicionar teóricamente el análisis desde una mirada crítica, contemporánea y situada ante los desafíos propios de América Latina frente a la Cuarta Revolución Industrial.

La importancia de este tema radica en que las tecnologías disruptivas no solo están transformando la operatividad interna de las instituciones públicas, sino que también están influyendo en las expectativas ciudadanas respecto a la participación, la rendición de cuentas y la calidad de los servicios gubernamentales. En regiones como América Latina y el Caribe, el desarrollo de infraestructuras digitales y la implementación de sistemas de gobierno electrónico han tenido un impacto positivo en los servicios públicos. Sin embargo, la limitada extensión de las redes de banda ancha y la escasa inversión en investigación y desarrollo plantean desafíos significativos que deben abordarse para aprovechar plenamente el potencial transformador de estas tecnologías.

El presente ensayo busca analizar cómo las tecnologías emergentes están reconfigurando los paradigmas de eficiencia y transparencia en la gestión pública, así como identificar las principales oportunidades y desafíos que surgen de este proceso. En particular, se examina el papel de herramientas tecnológicas como la inteligencia artificial, el blockchain y el big data en la optimización de procesos administrativos, la mejora de la rendición de cuentas y el fortalecimiento de los servicios públicos. Asimismo, se abordan temas relacionados con los riesgos de la brecha digital, las implicaciones éticas y la necesidad de marcos normativos más robustos para regular estas innovaciones. Estas reflexiones permiten responder a la pregunta de investigación: ¿cómo están transformando las tecnologías emergentes la gestión pública y cuáles son los principales desafíos que enfrentan las administraciones en su adopción?

Así, la tesis que se desprende es que las tecnologías emergentes no son herramientas neutras ni, de manera natural o lineal, propenden a la modernización, sino dispositivos de poder que reconfiguran las relaciones dentro de una sociedad política. Su implementación puede fortalecer las capacidades públicas y abrir nuevas formas de participación democrática, pero también puede profundizar asimetrías, excluir territorios y grupos vulnerables y consolidar lógicas de control opacas bajo el discurso eficientista. Esta problematización busca trascender el entusiasmo tecnocrático y explorar los dilemas que enfrenta el Estado ante la Cuarta Revolución Industrial: entre la innovación y la inclusión, entre la eficiencia y la legitimidad democrática.

Para ofrecer una visión integral del tema, el ensayo está organizado en cinco secciones principales. La primera introduce los conceptos básicos y el contexto histórico de la Cuarta Revolución Industrial, con énfasis en su impacto en la administración pública. La segunda sección detalla los criterios de selección del corpus bibliográfico y de los estudios de caso empleados. A continuación, la tercera sección realiza una revisión crítica del estado de la cuestión, identificando las tendencias y los debates actuales. En la cuarta sección se presentan las principales aportaciones del análisis, destacando las oportunidades y los desafíos identificados. Finalmente, se concluye con una reflexión sobre los hallazgos y sus implicaciones futuras para la formulación e implementación de políticas públicas.

2. Revisión de la Literatura

La selección del corpus para el análisis en cuestión se basó en tres criterios principales. En primer lugar, su relevancia teórica para comprender la transformación digital del sector público. En segunda instancia, la diversidad regional, con un énfasis particular en América Latina. Finalmente, en relación con la contribución empírica que puedan ofrecer mediante la revisión de casos concretos y de modelos de adopción tecnológica. Por sobre todo, se buscó construir un panorama amplio, desde múltiples miradas disciplinares, en el que se articulen perspectivas sobre innovación, capacidades institucionales, marcos normativos y desafíos éticos vinculados a la implementación de tecnologías emergentes en la administración pública.

2.1 Tecnologías emergentes y sus aplicaciones

El trabajo de Barragán Martínez (2023) se erige en una fuente fundamental por su análisis del impacto de las tecnologías emergentes en las dinámicas organizacionales y en la administración pública. Este autor destaca cómo herramientas como los algoritmos computacionales y el big data permiten la transición hacia una gobernanza pública inteligente, maximizando el bienestar social y mejorando los procesos de toma de decisiones. Sin embargo, un análisis crítico de esta propuesta evidencia que, aunque la tecnología brinda oportunidades significativas, su implementación enfrenta limitaciones estructurales y resistencia organizacional que dificultan los cambios. Este trabajo subraya la importancia de superar estas barreras para que las innovaciones tecnológicas sean realmente efectivas en la gestión pública.

Castillo Aucancela (2021) amplía esta discusión al presentar datos concretos sobre el crecimiento exponencial de los big data y los open data. La proyección de alcanzar 175 ZB de información global para 2025 sugiere un enorme potencial para transformar las administraciones públicas en términos de transparencia y eficiencia. Sin embargo, este volumen de datos plantea desafíos en la gestión, el análisis y el almacenamiento eficaces de la información. En este sentido, el caso de Ecuador, que muestra un uso limitado de datos abiertos con solo 1,987 datos liberados, evidencia cómo una infraestructura débil puede inhibir el desarrollo de estrategias tecnológicas. Por otro lado, el análisis del impacto económico del big data en Europa, con un crecimiento estimado de 230 mil millones de euros, pone de manifiesto el contraste entre regiones y resalta la necesidad de una planificación coherente en América Latina para generar valor público mediante estas tecnologías.

2.2 Brechas regionales y desafíos estructurales

Llanes-Font et al. (2020) profundizan en las brechas tecnológicas de América Latina y el Caribe, donde solo el 49,41% de las tecnologías disponibles se aprovecha adecuadamente. Este porcentaje evidencia una disparidad con otras regiones más avanzadas, lo que limita significativamente la digitalización de los servicios públicos. Además, la limitada capilaridad y la calidad de las infraestructuras de banda ancha en América Latina representan un obstáculo crítico. A pesar de estas limitaciones, políticas como las implementadas en Cuba desde 2017 ofrecen un ejemplo de cómo algunos países han comenzado a abordar estas deficiencias. Sin embargo, la efectividad de estas iniciativas depende de su capacidad para asegurar una infraestructura sostenible y accesible, así como para integrar estas políticas en un marco más amplio de transformación tecnológica regional. Además de los estudios regionales, se consideró relevante incluir el enfoque propuesto por Schwab (2023), quien conceptualiza la Cuarta Revolución Industrial como un fenómeno que exige repensar los marcos regulatorios, éticos y de gobernanza a nivel global.

2.3 Modelos exitosos y experiencias comparadas

El análisis de Cotino Hueso (2023) ofrece un contraste fundamental al estudiar el desarrollo digital en España, donde un alto porcentaje de los servicios digitales está diseñado tanto para la ciudadanía (87%) como para las empresas (94%). Este modelo exitoso refleja el impacto de una estrategia coherente y bien estructurada en la transformación digital. Asimismo, la tasa de uso del 73% de los servicios de administración electrónica en España demuestra cómo la accesibilidad tecnológica fomenta la participación ciudadana. Comparativamente, América Latina podría beneficiarse de la implementación de políticas inclusivas similares que promuevan competencias digitales y aumenten la adopción de servicios tecnológicos, siempre adaptadas a las particularidades y desafíos regionales.

2.4 Marcos teóricos explicativos

El marco teórico propuesto por Barras (1986) aporta una perspectiva indispensable para comprender los ciclos de innovación en servicios impulsados por tecnologías disruptivas. Su teoría del ciclo inverso de productos describe cómo estas tecnologías mejoran primero los procesos existentes antes de dar lugar a nuevos servicios, lo

que proporciona un esquema útil para analizar la evolución de la administración pública en el contexto de la Cuarta Revolución Industrial. Este modelo también destaca los riesgos de desigualdad tecnológica inicial, en particular en regiones como América Latina, donde la adopción de innovaciones es más lenta. Sin embargo, esta perspectiva sugiere que, con el tiempo y la planificación adecuadas, las tecnologías emergentes pueden cerrar estas brechas y generar mejoras significativas tanto en la eficiencia como en la calidad de los servicios públicos.

Miranda Gonçalves y Moreira Domingos (2021) ilustran el uso práctico de tecnologías disruptivas mediante el caso de la implementación de la blockchain en Brasil. Este ejemplo demuestra cómo una tecnología bien aplicada puede abordar problemas críticos de la gestión pública, como la corrupción, al promover la transparencia y la rendición de cuentas. No obstante, el caso de Brasil también refleja la necesidad de superar barreras culturales e institucionales para que estas herramientas sean ampliamente aceptadas y efectivas. La colaboración entre entidades como el Tribunal de Cuentas de la Unión y el Ministerio Público subraya la importancia de alianzas estratégicas para garantizar una implementación exitosa. Este modelo podría replicarse en otras regiones que enfrenten desafíos similares, adaptando las soluciones tecnológicas a sus contextos particulares.

El trabajo de Trujillo Sáez y Álvarez Jiménez (2021) enfatiza la importancia de la capacitación en competencias digitales para los empleados públicos, un aspecto clave para lograr transformaciones sostenibles en la administración. Sin esta formación, las instituciones públicas corren el riesgo de no aprovechar al máximo las tecnologías disponibles, lo que limita su capacidad para mejorar la eficiencia y promover la innovación. Este proceso de capacitación no solo contribuye a superar la resistencia al cambio, sino que también fomenta una cultura organizacional que valora la mejora continua y la adaptación tecnológica. La transformación digital, por lo tanto, no debe limitarse a la implementación de herramientas tecnológicas, sino que debe ir acompañada de iniciativas que fortalezcan las habilidades y competencias del personal público.

Finalmente, Valdez Zepeda (2019) profundiza en la comprensión del contexto administrativo en América Latina al ofrecer una perspectiva histórica sobre cómo los cambios en los paradigmas han influido en la gestión pública. Durante la década de los ochenta del siglo XX, una revolución administrativa redefinió procesos, prácticas y objetivos en las instituciones públicas, marcando un cambio hacia un modelo gerencial que contrastaba con los principios burocráticos predominantes en las décadas anteriores. Este contexto histórico es crucial para comprender los retos y oportunidades actuales de la Cuarta Revolución Industrial, ya que resalta la importancia de generar nuevos marcos administrativos que integren métricas de evaluación del desempeño, como los rankings, y promuevan incentivos positivos, como el prestigio institucional. Estas herramientas no solo fomentan la mejora continua, sino que también subrayan la necesidad de adaptarse a los cambios tecnológicos y sociales, maximizando así los beneficios de las tecnologías emergentes en la administración pública.

En conclusión, el análisis de este corpus revela múltiples perspectivas sobre cómo las tecnologías emergentes de la Cuarta Revolución Industrial están transformando la gestión pública. Aunque existen retos significativos, como las brechas tecnológicas y la resistencia al cambio, también es evidente el potencial de estas tecnologías para optimizar procesos, mejorar la transparencia y promover la eficiencia en la administración pública. Ahora bien, es importante declarar que, si bien el corpus revisado permite visualizar perspectivas y enfoques diversos sobre la relación entre tecnologías y gestión pública, también nos permite tener consciencia de algunos vacíos relevantes. En concreto, se identifica una escasez de estudios con enfoque longitudinal, una articulación limitada entre lo tecnológico y otras dimensiones, como la política-institucional, y la ausencia de reflexión sobre la gobernanza algorítmica o la soberanía digital como componentes críticos. Esta limitación representa una oportunidad para que futuros trabajos profundicen en los impactos estructurales de la Cuarta Revolución Industrial desde una perspectiva crítica, situada y orientada, por encima de todo, a la construcción de valor público.

3. Material y Métodos

Las tecnologías emergentes tienen el potencial de transformar significativamente la transparencia gubernamental al ampliar el acceso a la información pública y estandarizar su disponibilidad. Castillo Aucancela (2021) afirma que la combinación de big data y open data podría generar un impacto económico sustancial, estimado en 230 mil millones de euros en Europa. Este dato pone en evidencia el valor que estas herramientas pueden aportar al ámbito público, no solo optimizando operaciones, sino también fortaleciendo la confianza ciudadana al incrementar la rendición de cuentas. Sin embargo, estas proyecciones se enfrentan al desafío de su implementación efectiva, especialmente en regiones como América Latina, donde la infraestructura tecnológica y la cultura administrativa aún están rezagadas. Reflexionar sobre este potencial obliga a considerar cómo superar barreras culturales e institucionales que puedan obstaculizar los avances hacia una gobernabilidad más transparente.

A pesar de los beneficios proyectados, la implementación de estas tecnologías en América Latina presenta limitaciones significativas. Por ejemplo, Ecuador ha logrado liberar apenas 1,987 conjuntos de datos a través de su portal de datos abiertos, una cifra considerablemente modesta en comparación con las capacidades observadas

en regiones más avanzadas (Castillo Aucancela, 2021). Esto pone de manifiesto la necesidad de reforzar políticas públicas que promuevan el acceso abierto a los datos gubernamentales. Sin una visión estratégica y un compromiso político adecuado, la región se encuentra en una posición vulnerable frente a la transformación digital. Además, la falta de integración y coordinación en el manejo de estos recursos limita la capacidad de las administraciones públicas para aprovechar al máximo las tecnologías disponibles.

La interoperabilidad y el uso efectivo de big data presentan igualmente desafíos importantes. Sin modelos vinculantes y estandarizados, como lo evidencia la ausencia de un modelo único en Ecuador (Castillo Aucancela, 2021), las administraciones públicas enfrentan serias dificultades para garantizar la calidad y la consistencia de los datos liberados. Esto no solo compromete la eficiencia operativa, sino que también afecta la capacidad de generar conocimiento accionable a partir de la información disponible. La experiencia demuestra que una adecuada estandarización podría ser un catalizador para que las tecnologías de big data cumplan su promesa de mejorar la gestión pública, pero esto requeriría intervenciones coordinadas y regulaciones efectivas que incluyan a todos los actores clave.

En contraste con las dificultades observadas en América Latina, regiones como Europa han logrado aprovechar el big data para optimizar la toma de decisiones y generar confianza ciudadana mediante una mayor transparencia. Este éxito refuerza la necesidad de que América Latina adopte modelos de implementación tecnológica exitosos y los adapte a sus contextos específicos. Sin embargo, la transferencia de modelos no puede ser un proceso mecánico; debe incluir un análisis contextual que considere las condiciones políticas, económicas y sociales de cada país. La capacidad de América Latina para aprender de las mejores prácticas internacionales dependerá de su inversión en infraestructura y de su compromiso con la reducción de las brechas tecnológicas existentes.

La producción exponencial de datos en las últimas décadas refuerza la importancia de desarrollar estrategias que aprovechen este crecimiento para mejorar la transparencia gubernamental. Según Oszlak (2020), más del 90% de los datos actualmente disponibles se generó en el siglo XXI, lo que evidencia un panorama de oportunidades sin precedentes. Sin embargo, este flujo masivo de información plantea interrogantes sobre la capacidad de las administraciones públicas para almacenar, analizar y utilizar los datos de manera efectiva. La inercia burocrática, los recursos insuficientes y la falta de competencias especializadas son obstáculos que deben ser abordados para que esta explosión de datos beneficie realmente a las democracias y fortalezca su capacidad de respuesta a las demandas ciudadanas.

La brecha digital que enfrenta América Latina es evidencia clara de los desafíos estructurales de la región. Con un índice de aprovechamiento de tecnologías de apenas el 49,41% y limitaciones en la infraestructura de banda ancha (Llanes-Font et al., 2020), las administraciones públicas se ven restringidas en su capacidad para digitalizar servicios y conectarse de manera efectiva con la ciudadanía. Esta situación perpetúa desigualdades sociales, en particular en las comunidades rurales y desfavorecidas, limitando su acceso a servicios públicos esenciales. Además, las dificultades para garantizar una conectividad adecuada y asequible subrayan la necesidad urgente de políticas inclusivas que prioricen la expansión tecnológica en toda la región, evitando que el acceso a la tecnología se convierta en un factor de exclusión social.

España, en contraste, ha avanzado notablemente con un 87% de servicios digitales diseñados para la ciudadanía y un 94% para las empresas (Cotino Hueso, 2023). Este ejemplo subraya cómo una inversión estratégica y la implementación de políticas robustas pueden conducir a transformaciones significativas en la prestación de servicios gubernamentales. La accesibilidad tecnológica en España no solo ha mejorado la eficiencia operativa, sino que también ha fomentado una mayor participación ciudadana, un elemento clave para consolidar democracias más transparentes y responsables. América Latina podría aprender de esta experiencia, adaptando estrategias inclusivas y bien articuladas que fomenten la integración de las tecnologías emergentes en los procesos administrativos.

Un dato relevante sobre el contexto ecuatoriano evidencia cómo la resistencia cultural y organizacional afecta la capacidad de sus instituciones públicas para adoptar tecnologías. Barragán Martínez (2022) señala que, a partir de una encuesta realizada a 29 funcionarios públicos, se identificaron 15 soluciones tecnológicas replicables en áreas como el seguimiento de recursos, la gestión documental y el control de acceso. Aunque estas innovaciones representan un avance, la falta de escalabilidad y la limitada infraestructura tecnológica en Ecuador perpetúan la dependencia de sistemas obsoletos. Esto subraya la necesidad de implementar estrategias que no solo superen las barreras organizacionales, sino que también promuevan una transición hacia una infraestructura tecnológica más robusta y sostenible.

La evolución de las telecomunicaciones, en particular con el desarrollo de la tecnología 5G, representa una oportunidad transformadora para las infraestructuras digitales en América Latina. Según Oszlak (2020), esta tecnología es 40 veces más rápida que la 4G y su implementación podría revolucionar la conectividad regional. Sin embargo, para capitalizar este avance, será crucial superar las barreras estructurales existentes, como la limitada inversión en tecnología y la falta de coordinación entre los actores involucrados. Además, el desarrollo

de 5G plantea desafíos geopolíticos y económicos que podrían influir en la adopción de esta tecnología en la región, lo que requiere una planificación estratégica que considere no solo los beneficios técnicos, sino también las implicaciones políticas y sociales de su implementación.

La inteligencia artificial (IA) está emergiendo como un cambio paradigmático en la administración pública, con aplicaciones que van desde la formulación de políticas hasta la automatización de procesos. Según Sánchez Acevedo (2022), herramientas como Prometea y Pretoria han demostrado la capacidad de la IA para mejorar la eficiencia y la precisión en la toma de decisiones administrativas. Sin embargo, estos avances también conllevan riesgos éticos significativos, como los sesgos algorítmicos o el uso indebido de datos personales. Esto hace esencial la implementación de auditorías algorítmicas, como señalan Mota Sánchez y Herrera Expósito (2023), para garantizar que las tecnologías de IA operen dentro de marcos legales y éticos que respeten los derechos fundamentales de todas las personas.

Además, la efectividad de la IA en la administración pública está estrechamente vinculada con la formación de los servidores públicos. Según Trujillo Sáez y Álvarez Jiménez (2021), la capacitación continua y el desarrollo de competencias digitales son pilares esenciales para maximizar el potencial de estas tecnologías. Sin esta inversión en capital humano, las instituciones públicas corren el riesgo de subutilizar herramientas avanzadas y de no lograr los beneficios esperados de la digitalización. La experiencia internacional, como en el caso de AuroraAI en Finlandia (Chaves, 2020), demuestra que la integración exitosa de la IA depende de políticas que equilibren la innovación tecnológica con la capacitación de las personas responsables de implementarla.

Ejemplos prácticos como los sistemas de aprendizaje profundo desarrollados por DeepMind, que demostraron ser capaces de resolver tareas complejas con gran éxito (Oszlak, 2020), muestran que el potencial de la IA va más allá de la automatización básica. Estas aplicaciones podrían replicarse en operaciones administrativas para predecir problemas sociales, optimizar recursos y mejorar la efectividad de las políticas públicas. No obstante, su implementación debe supervisarse cuidadosamente para evitar posibles impactos negativos en la privacidad y la equidad.

La gobernanza digital también enfrenta desafíos éticos y jurídicos inherentes a las particularidades del entorno digital. Chaves (2020) señala que la privacidad y el control de los datos personales son cuestiones críticas en un contexto de creciente digitalización. Asimismo, Mota Sánchez y Herrera Expósito (2023) destacan la importancia de las auditorías algorítmicas como herramientas para garantizar la transparencia y la responsabilidad en el diseño y el uso de sistemas de IA. Casos como las sanciones impuestas en Colombia en 2019 por violaciones a la protección de datos (Sánchez Acevedo, 2022) subrayan la necesidad urgente de marcos regulatorios sólidos y efectivos para proteger los derechos de las personas en la esfera digital.

Finalmente, los desafíos que enfrenta América Latina en materia de inversión en investigación y desarrollo constituyen un impedimento significativo para la adopción de tecnologías emergentes. Países como México, que invierten solo el 0.4% de su PIB en estas áreas (Cabello y Ortiz, 2013), lo que disminuyó a 0.27% en una década según el Banco Mundial, no pueden competir con economías que priorizan el desarrollo tecnológico. Este retraso no solo limita la competitividad regional, sino también la capacidad de las administraciones públicas para implementar herramientas disruptivas que transformen sus operaciones. Sin un cambio en las prioridades presupuestarias, América Latina corre el riesgo de quedar aún más marginada en el contexto global de la Cuarta Revolución Industrial.

En conclusión, aunque las tecnologías emergentes abren puertas potenciales a la transparencia, la eficiencia y la optimización de los procesos administrativos, su implementación está condicionada por factores estructurales, culturales y éticos que no pueden ignorarse. La Cuarta Revolución Industrial es más que la introducción de nuevas herramientas; esta introducción invita a reconfigurar profundamente la arquitectura del Estado, su legitimidad y sus capacidades de acción. Esto, lejos de ser neutral, depende de cómo, para qué y en qué condiciones se incorporen estas tecnologías.

Desde una mirada crítica latinoamericana, el mayor riesgo en esto no es de carácter técnico, sino más bien político. Lo anterior, en la medida en que la ausencia de marcos ético-políticos sólidos puede convertir la transformación digital en una (nueva) fuente de exclusión, dependencia y concentración de poder, disfrazada de modernización eficiente. En este sentido, pensar que el desafío es solo implementar tecnología es, sencillamente, limitado, ya que el verdadero sentido está en construir gobernanzas digitales justas, democráticas y, no menos importante, soberanas, donde el interés público no esté subordinado a lógicas de mercado ni a una poca transparencia algorítmica. Estamos en un punto de inflexión clave, donde el devenir de la gestión pública y su eventual dirección dependen de la capacidad de los Estados para usar estas nuevas herramientas tecnológicas como instrumentos de equidad, deliberación y bienestar colectivo, mas no como instrumentos de control, segmentación o desposesión.

4. Resultados

La Cuarta Revolución Industrial está provocando transformaciones profundas en la gestión pública, donde tecnologías emergentes como la inteligencia artificial (IA) y el big data desempeñan un papel clave en la optimización de procesos administrativos y en la mejora de la eficiencia en la toma de decisiones. Según Criado (2021), la IA no solo facilita la automatización de tareas rutinarias, sino que también ofrece un potencial significativo para el análisis predictivo, lo que permite a las administraciones anticipar tendencias y atender de manera proactiva las necesidades de la ciudadanía. A pesar de estos avances, su implementación plantea desafíos éticos y legales, como los sesgos algorítmicos, que podrían perpetuar desigualdades existentes si las bases de datos contienen errores o sesgos. Para abordar estos riesgos, Mota Sánchez y Herrera Expósito (2023) proponen utilizar auditorías algorítmicas como herramientas esenciales para garantizar la transparencia y la equidad en el uso de la IA. Este enfoque no solo refuerza la confianza pública, sino que también asegura que la tecnología opere dentro de marcos legales que respeten los derechos fundamentales.

Una de las principales contribuciones de la IA a la gestión pública es su capacidad para transformar el análisis predictivo en una herramienta estratégica. Por ejemplo, Boma (2023) destaca que los algoritmos avanzados pueden predecir el mantenimiento de infraestructuras, optimizar recursos y reducir significativamente los costos operativos. Esta aplicación, sin embargo, requiere bases de datos fiables y actualizadas, lo que supone un desafío para muchas administraciones públicas, especialmente en regiones con infraestructura tecnológica limitada. Además, Criado (2021) señala que la automatización de tareas rutinarias, como la limpieza de datos y la generación de informes, libera tiempo valioso para que el personal público se enfoque en actividades estratégicas que requieren juicio humano. Este impacto positivo en la eficiencia organizacional subraya la necesidad de capacitar a los empleados para trabajar eficazmente con estas herramientas tecnológicas.

La automatización impulsada por la IA también está introduciendo cambios significativos en los perfiles laborales del sector público. Mediavilla y Sierra (2016) argumentan que estas tecnologías no solo transformarán cómo trabajamos, sino también el tipo de ocupaciones que surgirán, creando nuevas oportunidades de empleo. Este fenómeno también suscita interrogantes sobre la redistribución de tareas y el impacto de la automatización en los empleos existentes, en los que los sectores más vulnerables podrían experimentar desplazamientos laborales. Por lo tanto, resulta crucial acompañar estas innovaciones con políticas de transición laboral y programas de reentrenamiento que minimicen el impacto social y económico de la automatización en el empleo público.

No obstante, el uso de algoritmos en la toma de decisiones públicas conlleva riesgos de discriminación algorítmica. Mota Sánchez y Herrera Expósito (2023) advierten que estos riesgos se deben a la posibilidad de que las bases de datos subyacentes contengan sesgos o errores que afecten la imparcialidad del sistema. Aunque las auditorías algorítmicas prometen mitigar este problema, también plantean desafíos en términos de costos y de la necesidad de personal especializado para implementarlas y supervisarlas de manera eficaz. Este aspecto resalta la importancia de priorizar tanto la sostenibilidad financiera de estas iniciativas como la formación ética de los equipos encargados de desarrollar y gestionar dichas tecnologías.

En este contexto, la falta de capacidades técnicas en muchas administraciones públicas de América Latina limita severamente la adopción masiva de la IA (Salvador Serna, 2021). Para revertir esta situación, se requiere una combinación estratégica de inversiones en infraestructura tecnológica, programas de capacitación intensiva y el fortalecimiento de alianzas con los sectores académico y privado. De lo contrario, las desigualdades tecnológicas entre regiones podrían incrementarse, lo que dificultaría la capacidad de los países menos desarrollados para aprovechar las tecnologías emergentes en la gestión pública.

La digitalización de los servicios públicos ha demostrado ser un elemento crucial para aumentar la transparencia y promover la participación ciudadana. Mejía Márquez (2021) destaca el notable avance de México, donde casi el 90% de las transacciones gubernamentales se inician en línea. Este desarrollo contrasta significativamente con la limitada digitalización en Perú, donde solo el 15.1% de los trámites puede iniciarse de forma digital. Este contraste subraya la importancia de una infraestructura tecnológica robusta y de políticas públicas coherentes para impulsar la inclusión digital y cerrar las brechas regionales. Sin embargo, la dependencia de tecnologías digitales también genera preocupaciones sobre la exclusión de aquellos sectores que aún no tienen acceso adecuado a estas herramientas, como las poblaciones rurales y de bajos ingresos.

La digitalización no solo reduce los tiempos de espera en la prestación de servicios, sino que también disminuye los costos operativos tanto para la ciudadanía como para las administraciones (Mejía Márquez, 2021). Este impacto positivo se extiende más allá de la eficiencia operativa, fomentando una mayor confianza en las instituciones públicas al hacer que los procesos sean más accesibles y transparentes (Miranda Gonçalves & Moreira Domingos, 2021). Sin embargo, Llanes-Font et al. (2020) advierten que muchas administraciones de América Latina carecen de estrategias integrales para implementar servicios digitales, perpetuando un rezago que podría ampliarse si no se toman medidas inmediatas.

En el ámbito de la innovación tecnológica para la gestión pública, la blockchain se presenta como una herramienta clave para combatir la corrupción y reforzar la transparencia. En Brasil, Miranda Gonçalves y Moreira Domingos (2021) documentan cómo esta tecnología ha transformado procesos administrativos sensibles, como las contrataciones públicas, garantizando la integridad de los datos mediante registros inmutables. A pesar de su potencial, Salvador Serna (2021) advierte sobre los altos costos de implementación y la necesidad de capacitar al personal en el uso de esta tecnología, aspectos que deben abordarse para garantizar su efectividad.

Por otro lado, el crecimiento exponencial de los datos globales, proyectado para alcanzar los 175 zettabytes en 2025 (Castillo Aucancela, 2021), presenta tanto oportunidades como desafíos. Barragán Martínez (2023) señala que el uso eficaz de big data puede transformar la gestión pública mediante un análisis más profundo de las necesidades sociales. No obstante, Llanes-Font et al. (2020) señalan que el acceso limitado a la banda ancha en América Latina reduce la capacidad de las administraciones para capitalizar estos avances. Este contexto demanda inversiones sustanciales en infraestructura tecnológica y en políticas públicas que prioricen la conectividad para cerrar la brecha digital existente entre América Latina y otras regiones.

Finalmente, más allá de la implementación tecnológica, la transformación digital del sector público requiere cambios estructurales profundos y el fortalecimiento de las competencias del personal. Salvador Serna (2021) enfatiza la importancia de programas de formación en plataformas de e-Training que faciliten la actualización continua de las habilidades. Sin embargo, estos programas deben ir acompañados de estrategias efectivas de gestión del cambio que superen la resistencia organizacional típica de las estructuras burocráticas tradicionales (Barragán Martínez, 2023). La transformación digital, como destaca Delgado Fernández (2020), no solo afecta los modelos de negocio, sino también la interacción y la experiencia del usuario, lo que evidencia la necesidad de un enfoque centrado en las personas para maximizar el impacto de estas tecnologías.

En suma, los casos y evidencias analizados nos permiten sostener que la adopción de tecnologías emergentes en la gestión pública, en el contexto de la 4RI, no puede pensarse de manera aislada del desarrollo de capacidades estatales estratégicas. La efectividad de herramientas como la inteligencia artificial, el blockchain o el big data no se reduce únicamente a su potencial técnico, sino también a la capacidad de los Estados para integrarlas de forma ética, sostenible y situada. Este no es menor: nos da cuenta de una tensión entre la eficiencia y la equidad. Mientras las tecnologías prometen agilizar procesos y reducir costos, su implementación puede terminar por ampliar las brechas o solidificar formas de exclusión si no se acompañan de marcos normativos sólidos, inversión en talento público y una visión política inclusiva. Si bien autores como Schwab (2023) destacan el potencial transformador de estas tecnologías, nuestro análisis sugiere que su implementación sin marcos ético-políticos sólidos puede profundizar desigualdades estructurales y erosionar las capacidades públicas en lugar de fortalecerlas. Así, la invitación es a entender la transformación digital como un medio para fortalecer el valor público y democratizar la acción estatal, no como un fin en sí mismo.

5. Conclusiones

El análisis realizado en este ensayo ha logrado alcanzar el objetivo principal, que consistía en explorar cómo las tecnologías emergentes de la Cuarta Revolución Industrial están transformando la gestión pública, en particular en términos de eficiencia, transparencia y participación ciudadana. A lo largo del texto, se ha demostrado que herramientas como la inteligencia artificial, el blockchain y el big data son agentes centrales en la reconfiguración de los procesos administrativos y en la optimización de la toma de decisiones. Sin embargo, también se han identificado barreras significativas que limitan su adopción efectiva, especialmente en regiones como América Latina, donde persisten brechas digitales, resistencia institucional al cambio y una infraestructura tecnológica insuficiente. Esta investigación ha permitido visualizar las oportunidades y desafíos inherentes a estas innovaciones, así como evaluar su impacto desde una perspectiva comparativa y mediante casos específicos.

Entre los hallazgos más relevantes, se destaca que el potencial transformador de las tecnologías emergentes ha sido particularmente evidente en contextos como el europeo. Por ejemplo, en España se han alcanzado altos niveles de digitalización, con un 87% de los servicios públicos accesibles para la ciudadanía y un 94% para las empresas, lo que ha incrementado la participación ciudadana y mejorado la transparencia. En contraste, América Latina enfrenta importantes limitaciones estructurales que restringen el aprovechamiento de estas tecnologías. El índice de utilización de tecnologías en la región es de tan solo el 49,41%, una cifra que evidencia tanto la desigualdad tecnológica como la necesidad de estrategias más inclusivas y de inversiones bien planificadas. Asimismo, el caso de Brasil en la implementación de blockchain refleja cómo estas herramientas pueden ser útiles para combatir la corrupción y fortalecer la rendición de cuentas, aunque su adopción masiva requiere superar barreras culturales y logísticas. Este contraste regional no solo subraya la importancia de políticas públicas coherentes, sino también la necesidad de adaptar las soluciones tecnológicas a las realidades económicas y sociales de cada país.

La investigación también ha puesto de manifiesto cómo los desafíos éticos y jurídicos asociados a las tecnologías emergentes plantean nuevas preguntas sobre la gobernanza tecnológica. Casos como los riesgos de la discriminación algorítmica en la inteligencia artificial exigen una regulación robusta y la implementación de auditorías algorítmicas para garantizar que estas herramientas operen de manera justa y equitativa, protegiendo los derechos fundamentales. Asimismo, la gestión de grandes volúmenes de datos, como los 175 zettabytes proyectados para 2025, plantea interrogantes sobre la capacidad de las administraciones públicas para aprovechar estas oportunidades sin comprometer la privacidad de los ciudadanos. En este sentido, se identificaron como factores clave la capacitación continua de los empleados públicos en competencias digitales y la elaboración de marcos normativos que equilibren la innovación con la protección de los derechos.

En el contexto más amplio de la investigación, los resultados obtenidos dialogan directamente con estudios previos que destacan el impacto positivo de tecnologías disruptivas, como el big data, en la transformación de los servicios públicos. Autores como Criado han señalado el valor de la inteligencia artificial en la automatización de tareas y en el análisis predictivo, mientras que otros, como Llanes-Font et al., han reforzado la percepción de que las barreras estructurales en América Latina limitan dicho potencial. Así, este trabajo contribuye a un entendimiento más integral de la cuestión al ofrecer no solo un análisis técnico de las capacidades tecnológicas, sino también una evaluación crítica de los retos regionales, culturales y éticos que condicionan su implementación. Además, al vincular hallazgos empíricos con teorías como el modelo del ciclo inverso de productos de Barras, la investigación proporciona un marco conceptual útil para futuras exploraciones sobre la innovación tecnológica en el sector público.

A pesar de los avances logrados, esta investigación presenta limitaciones que deben considerarse. Por un lado, la dependencia de estudios de caso específicos impide una generalización completa de los hallazgos, particularmente en regiones o sectores que quedaron fuera del análisis. Por otro lado, la falta de datos cuantitativos propios limita la capacidad de medir con precisión el impacto económico y social de las tecnologías emergentes. Asimismo, debido a la rápida evolución tecnológica, algunos de los resultados presentados podrían quedar obsoletos en un futuro cercano, lo que resalta la importancia de investigaciones continuas para mantener la pertinencia del análisis realizado.

En cuanto al futuro de esta línea de investigación, se identifican múltiples áreas que requieren atención adicional. Será esencial llevar a cabo análisis longitudinales sobre el impacto de la automatización y la inteligencia artificial en la sostenibilidad del empleo público, explorando no solo las oportunidades de reentrenamiento laboral, sino también las tensiones sociales que pueden surgir de la transformación tecnológica. Del mismo modo, estudiar casos de implementación tecnológica en países con estructuras políticas descentralizadas podría ofrecer nuevos aprendizajes sobre los factores que favorecen el éxito de estas iniciativas. Además, dado el creciente papel de la gobernanza digital, los futuros estudios deberían centrarse en diseñar marcos normativos que protejan los derechos fundamentales sin frenar la innovación tecnológica y en abordar especialmente los dilemas éticos asociados al uso de la inteligencia artificial y del big data en el ámbito público.

En términos de nuestra reflexión propia, la Cuarta Revolución Industrial debe ser comprendida no solo como un proceso de innovación tecnológica que traerá una modernización y una optimización lineales del Estado, sino más bien como un fenómeno que redefine su rol, sus formas de legitimidad y su vinculación con la ciudadanía. Así, defendemos un modelo de transformación digital en el que lo público sea lo medular, en el sentido de que promueva principios como la soberanía tecnológica, la justicia algorítmica, la transparencia deliberativa y la equidad estructural. Estos son particularmente relevantes en la región latinoamericana, y requiere superar el benchmarking y la copia de modelos externos, y en su lugar, pensar este momento como una oportunidad para construir un nuevo modelo de Estado, donde la tecnología, en tanto instrumento no neutral, es decir, con capacidad de amplificar o erosionar capacidades estatales, este al servicio de la construcción de un Estado más inclusivo, resiliente y democrático.

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